ALUMINIUM AND ITS ALLOYS

CALYPSO WORKS.

ALUMINIUM
AND ITS ALLOYS

THEIR PROPERTIES, THERMAL TREATMENT AND INDUSTRIAL APPLICATION

BY

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TRANSLATORS' NOTE

In this translation of Col. Grard's book on "Aluminium and its Alloys," the original text has been adhered to, with the exception of certain of the appendices. Certain of the conditions of the French aeronautical specifications, dealing with sampling and identification of material, have not been considered of sufficient interest to English readers to warrant their inclusion, but the clauses dealing with methods and results of tests have been given.

The centigrade scale of temperatures has been retained throughout the book.

In statistics of a general nature—as, for instance, in the case of approximate output—the tonne and ton have been regarded as equivalent. In exact statistics, however, an accurate conversion has been made, and both sets of values given.

Where prices are given, the rate of exchange has been taken as twenty-five francs to the pound sterling, whatever the date of the statistics in question.

The Tensile Strength and Elastic Limit are expressed in kilogrammes per square millimetre and in tons per square inch—at the express wish of the author, both sets of values are given throughout the book, in the tables and diagrams.

In the case of Hardness and Cupping Tests, no conversion has been attempted, the metrical values being in general use in this country. As regards Shock Resistance also, no conversion has been attempted. On the Continent the term "Resilience" is employed to denote the energy absorbed in impact, expressed in kilogramme-metres per square centimetre of cross section of the test piece at the bottom of the notch, whilst in this country, it is employed to denote a different property. The area of cross section at the foot of the notch

is not taken into consideration, but the Shock Resistance is expressed simply by the energy, in foot-pounds, absorbed by impact upon a test piece of standard dimensions.

Assuming that the conversion from kilogramme-metres per square centimetre to foot-pounds is an arithmetical possibility, the figures would still not be comparable, as the numerical value depends to a very great extent on the precise form of the test piece employed, especially on the angle and radius at the foot of the notch, which is different in British and Continental practice.

The translators would wish to express their thanks to Dr. A. G. C. Gwyer, Chief Metallurgist to the British Aluminium Co., Ltd., for his valuable advice and for his assistance in the reading of proofs.

C. M. Phillips.
H. W. L. Phillips.

Warrington,
November, 1920.

AUTHOR'S NOTE

For carrying out the numerous tests required for this work, we have utilised the following Government laboratories :—

Le Laboratoire d'Essais du Conservatoire national des Arts et Métiers (chemical analyses, mechanical tests).

Le Laboratoire d'Essais de la Monnaie et des Médailles (chemical analyses).

Le Laboratoire de la Section technique de l'Artillerie (chemical analysis).

Le Laboratoire de l'Aéronautique de Chalais-Meudon (mechanical tests and micrography).

The results, from which important deductions have been made, possess, therefore, the greatest reliability.

We must also thank the following private laboratories :—

Les Laboratoires de la Société Lorraine-Dietrich (heat treatments and mechanical tests),

Les Laboratoires de l'Usine Citroën (mechanical tests and micrography),

for the readiness with which they have placed their staff and laboratory material at the disposal of the Aéronautique. By their assistance tests were multiplied, inconsistencies removed, and the delays, incidental to the carrying out of this work, minimised.

Thanks also to the courtesy of the Société de Commentry-Fourchambault, M. Chevenard, engineer to the Company, has investigated, by means of the differential dilatometer of which he is the inventor, the critical points of certain alloys, whose thermal treatment (quenching and reannealing) is of vital importance.

INTRODUCTION

GENERAL ARRANGEMENT OF CONTENTS

THE chief characteristic of aluminium is its low density, being second only to magnesium, and, for this reason, it is valuable for aircraft. Aluminium would be ideal if this lightness could be combined with the mechanical properties of the Ferrous metals.

The ore, from which alumina, for the preparation of the metal, is extracted, is widely distributed, and France is particularly favoured in this respect.

Whatever the method of working and thermal treatment, pure aluminium only possesses a low strength, which prohibits its use for articles subjected to great stresses. Fortunately, certain of the mechanical properties of the metal can be improved by the addition of other constituents, and in some of the alloys thus formed the density is little changed. These are the so-called light alloys, in which aluminium is a main constituent, and which can be divided into :—

(i) Light alloys of low strength.
(ii) Light alloys of great strength.

In others, aluminium is present in such small quantity that the alloy loses its characteristic lightness, to the advantage of some of the mechanical properties. The most important are those in which copper is the principal constituent. These are

(iii) Heavy alloys of great strength.

The alloys of aluminium, which can thus be divided into three groups, are very numerous, and there can be no question of considering them all. In each group we shall study the ones which seem the most interesting—those in which aluminium plays an important part. We shall not lay much

stress upon those in which aluminium is of minor importance.

Adopting the classification here given, arbitrary, no doubt, but which, from the aviator's point of view, has its value, since it puts side by side the properties of lightness and strength, we shall consequently arrange this work according to the following scheme :—

Book I.—Aluminium, comprising two parts :—

Part I. Production of aluminium.
Part II. Properties of aluminium.

Book II.—Alloys of aluminium, comprising three parts :—

Part III. Light alloys for casting purposes.
Part IV. Light alloys of great strength.
Part V. Heavy alloys of great strength.

Throughout, a large number of tests has been made on each type. In particular, an exhaustive study has been carried out on the properties as functions of cold work and annealing, and on the hardness at all temperatures. The reliability of the results is guaranteed by the standard of the testing laboratories, and by the reputation of the experimenters.

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Aluminium and its Alloys

PART I

PRODUCTION OF ALUMINIUM

CHAPTER I

METALLURGY OF ALUMINIUM

ALUMINIUM is prepared by the electrolysis of alumina dissolved in fused cryolite. The electric energy is derived from water-power. The essential materials for the process are therefore

(i) Alumina.
(ii) Cryolite.

ALUMINA.

Alumina is prepared from bauxite [$(Al, Fe)_2O_3 2H_2O$] or from certain clays [$Al_2O_3.2SiO_2$].

(a) *From Bauxite.*

Bauxite is a clay-like substance, whitish when silica is predominant, or reddish when oxide of iron is largely present. It is found in great quantity in France, in the neighbourhood of the village of Baux, near Arles (hence the name, bauxite), and more commonly in the Departments of Bouches-du-Rhône, Gard, Ariège, Hérault, and Var. It is found in Calabria, Iceland, Styria, Carniola, and in the United States of America in Georgia, Arkansas, Alabama, and Tennessee.

Commercial bauxite has the following composition :—*

Alumina (Al_2O_3) .	57 %	A premium of ·20 to ·40 francs per kilo (roughly 1d. to 2d. per lb.) was, in 1909, paid for each per cent over 60 %.
Silica (SiO_2) . .	3 %	If below 2 %, a premium of ·20 fr. per kg. (roughly 1d. per lb.) was paid per ·1 %.

* Lodin, "Annales des Mines," Nov., 1909.

Iron Oxide (Fe_2O_3) .	14 %	For each per cent above this value, up to the maximum allowed, 17 %, ·20 fr. per kg. (roughly 1d. per lb.) was deducted. Some works allow as much as 25 % Fe_2O_3.

White bauxites are chiefly used for the production of aluminium sulphate and the alums. Red bauxites form the raw material for the preparation of alumina, and therefore of aluminium. Intermediate or refractory bauxites, fused in an electric furnace, give artificial corundum.

Bauxite is treated either by Deville's method or by that of Bayer, the latter being almost exclusively employed. A third method depends upon the production of aluminium nitride. This is obtained by heating bauxite in air to 1800°–1900° in an electric furnace. It is then decomposed in an autoclave in presence of soda solution, giving (i) ammonia, used as a manure in the form of its sulphate, (ii) sodium aluminate, from which commercially pure alumina can be obtained.

(b) *From Clay.*

Clays are treated either by the Cowles-Kayser or by the Moldentrauer process, yielding alumina from which aluminium is prepared by electrolysis.

CRYOLITE.

Cryolite, which is so called on account of its high fusibility, is a double fluoride of aluminium and sodium of the formula $Al_2F_6.6NaF$. It is obtained from Western Greenland, where it occurs in beds up to one metre thick, but the high price of this material has led to the manufacture of synthetic cryolite, using calcium fluoride (fluor-spar), which is found in considerable quantities.

ELECTRIC FURNACES.

The furnace consists of a vat, containing electrodes (anodes), and a conducting hearth (the cathode) sloping towards the tapping hole. Aluminium, formed by electrolysis of the alumina, collects on the floor of the vat; oxygen is liberated at the anode, which it attacks, forming carbon monoxide and finally carbon dioxide.

The current is used at a potential difference of 8 to 10 volts, and at a density of 1·5 to 3 amps. per square centimetre of electrode. The furnace is regulated by raising or lowering the electrodes, or by varying the quantity of alumina. When

the latter is present in small quantities, the fluorides decompose, and the voltage (normally 8–10 volts) rises. This is indicated by the change in intensity of a lamp. In this case sodium is formed at the cathode, and has deleterious effects on the quality of the metal.

METHOD OF TAPPING ALUMINIUM.

Since aluminium is very easily oxidised, it cannot be subjected to a final refining process, but must possess, at this early stage, its commercial purity. It is therefore essential to avoid oxidation during the manufacturing process, and the cryolite,

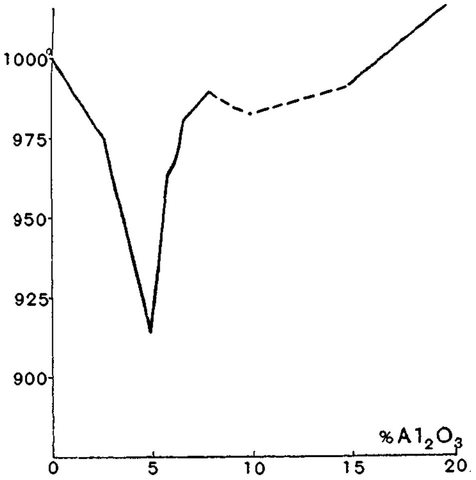


FIG. 1.—Melting-point Curve of Mixtures of $Al_2F_6.6NaF$ and Al_2O_3. (*Pryn.*)

containing alumina in solution, furnishes the means to that end. The metallic aluminium must not float, but sink to the bottom of the vat, where the fused salts protect it against oxidation. The salts must have, therefore, a lower density than the metal.

The theory of the preparation of the metal is made clear by a study of the melting-point curve of mixtures of cryolite ($Al_2F_6.6NaF$) and alumina, due to Pryn.*

Pure cryolite melts at 1000°, and the mixture of maximum fusibility (915°) consists of 95 % cryolite with 5 % alumina.

As the alumina content increases from 5 to 20 %, the melting point rises from 915°–1015°, the curve of fusibility consisting of portions of straight lines of varying slope.

* Pryn, "Mineral Industry," Vol. XV, p. 19.

Certain definite mixtures of cryolite, calcium fluoride or aluminium fluoride, and alumina have still lower melting points, the limiting value being 800° (Hall). In practice the melting point of the bath ranges from 900°–950°; it is therefore evident that the manufacturer has a choice of mixtures which will fulfil these conditions.

The respective densities of the cryolite mixture and of aluminium are:—

Cryolite mixture .	solid,	2·92
	liquid,	2·08
Aluminium . .	solid,	2·6
	liquid,	2·54

which satisfy the conditions above mentioned.

The furnace is tapped about every forty-eight hours. The liquid flows first into a receiver, in which the fluorides carried over are retained in the solid state, and from this vessel into moulds, giving ingots which can easily be divided.

Output.

According to Flusin, the output is as follows:—

210 kg. to 275 kg. of aluminium per kilowatt-year (i.e. 463 lb.–606·1 lb. per kw. year),

or, 154–200 kg. per "Force de cheval" year (i.e. 344·1–447 lb. per horse-power year),

which works out at:—

31–41 kilowatt hours per kg. of aluminium (i.e. 14·1–18·7 kw. hours per lb.),

assuming an average efficiency of 70 %, and a maximum efficiency of 78 %.

Consumption of Material.

Alumina per kg. of aluminium: theoretically 1·888 kg.
practically 2·0 kg.;

formerly this figure was higher, but then the voltage was 15 to 20 v. (i.e. 1·888 tons and 2·0 tons of alumina per ton of aluminium, respectively).

Cryolite, per kg. of aluminium 0·150 kg. on an average (i.e. 3 cwt. cryolite per ton of aluminium).

Calcium and aluminium fluorides, per kg. of aluminium, 0·200 kg. (i.e. 4 cwt. per ton of aluminium).

Anodes, per kg. of aluminium, 0·8 to 1·0 kg. (i.e. 16 cwt.–1 ton per ton of aluminium),

From these data we can draw the following conclusions concerning the cost price. For the production of a ton of aluminium two tons of alumina are required and also one ton of carbon for the electrodes; while, for the production of the alumina itself, six tons of carbon are required. Since alumina is made near the spot where bauxite is found, it is necessary to consider the effect of the following transport charges upon the cost price:—

(i) Carriage of carbon to alumina works.
(ii) Carriage of carbon to aluminium works.
(iii) Carriage of alumina to aluminium works.

It is evident that those aluminium works which can obtain only hydraulic power locally, so that the transport charges, just mentioned, are heavy, are at a disadvantage in competing with works more favourably situated. The French aluminium works are especially favoured in this respect.*

ROLLING OF ALUMINIUM.

The ingots of aluminium are first melted in a furnace—often a revolving furnace, heated by gaseous fuel. The aluminium is then cast into slabs, which, in France, usually are of the following dimensions:—

(1) 80 kg.=0·55m. × 0·65m. × 0·08m.(21·6in. × 25·5in. × 3·15in.)
(2) 55 kg.=0·56m. × 0·66m. × 0·055m.(22·0in. × 25·9in. × 2·16in.)
(3) 27 kg.=0·35m. × 0·7m. × 0·04m.(13·8in. × 27·5in. × 1·57in.)

* Lodin established in the following manner the cost price in 1909:—

Alumina	1·950 kg. per kg. of Al	at	0·3 fr.	per kg.	0·585 fr.
Cryolite	0·125 kg.	,, ,,	0·6	,,	0·075 ,,
Electrodes	0·800 kg.	,, ,,	0·35	,,	0·280 ,,
Labour	0·025	,, ,,	5	,,	0·125 ,,
Electrical energy	40 kw. at ·006 fr. per kw.				0·240 ,,
				Total	1·305 fr.

per kg. of aluminium (i.e. roughly 6d. per lb.), to which, in general, transport charges must be added.

In the United States of America, the cost price of aluminium in 1906 would be, according to "The Mineral Industry," roughly 7½d. per lb. The price of aluminium has varied in a very noticeable manner since 1855, having passed through the following stages:—

	Fr. per kg.	Price per lb.
1855	1230	£22 5 3
1886	78	1 8 3
1890	19	6 10
1900	2·5	11
1908 (end of Heroult patents)	2	8½
1908–1914	1·5–2·1	6½–9
1916	6·8–7·0	2/6–2/6½

Aluminium is often cast into billets, frequently cylinders of 3 kg. in weight, 80 cm. high and 4 cm. in diameter (31·5 in. × 1·57 in.). The slabs or billets are cast from a mixture of ingots, and therefore a fresh analysis must be carried out to give the quality.

The temperature of casting is usually 750–775°, and the temperature of rolling 400–450°, roughly the temperature of smouldering wood.

ROLLING OF ALUMINIUM INTO THIN SHEETS.*

Aluminium can be rolled into sheets ·01 cm. thick (·0039 in.), similar to tinfoil. The process has been carried out by Drouilly —a strip initially 0·35 cm. thick (·138 in.) is rolled in the cold to 0·04 cm. (·016 in.); the reduction is made in six passes with intermediate annealing. The second stage consists in reducing the sheets to a thickness of ·01 cm., either by means of blows from a 150 kg. (roughly 3 cwt.) pneumatic hammer, giving 300 blows per minute, or by further rolling.

EXTRUSION.

Tubes and sections can be obtained by extrusion.†

ALUMINIUM DUST.

Powdered aluminium, in the form of paint, is applied to finished metallic goods, resulting in a galvanisation effect. For literature on this subject, the work of Guillet (loc. cit.) should be consulted.

* For details of process, see Guillet, "Progrès des Métallurgies autreque la Sidérurgie et leur État actuel en France," pp. 264-268. (Dunod et Pinat, 1912.)

† Cf. Breuil, "Génie Civil," 1917. Nos. 23 and 24.

CHAPTER II

WORLD'S PRODUCTION

I. Bauxite.

The French Minister of Commerce gives the following particulars concerning the world's production of bauxite :—*

	U.S.A.		France		Great Britain		Italy	
	Tonnes	Tons	Tonnes	Tons	Tonnes	Tons	Tonnes	Tons
1910	152,070	149,698	196,056	193,358	4,208	4,142	—	—
1911	158,107	155,610	254,831	250,800	5,103	5,022	—	—
1912	162,685	160,110	258,929	254,836	5,882	5,789	—	—
1913	213,605	210,228	309,294	304,410	6,153	6,056	6,952	6,842

It is therefore evident that up to 1914, there were only two important centres in the world for the production of bauxite, namely, France and the United States of America.

Position in 1913.

The distribution of bauxite in 1913 (527,536 tons) is shown in the following diagram (Fig. 2) :—

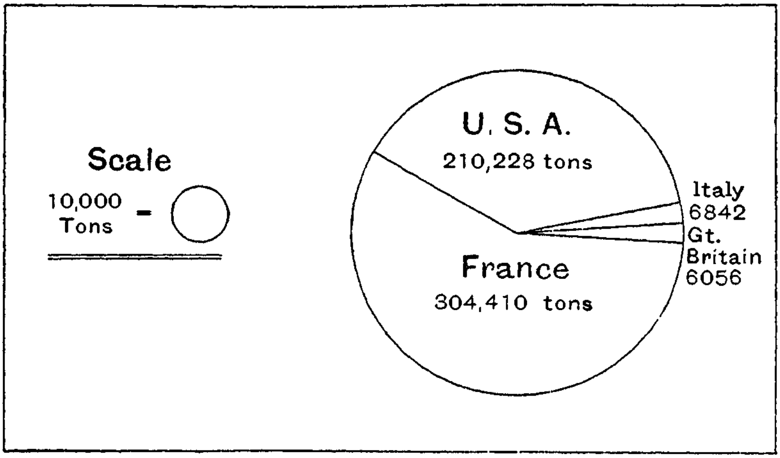


Fig. 2.—Distribution of Bauxite.

* Vol. I, "Rapport général sur l'industrie française, sa situation, son avenir," based on the work of sections of the "Comité consultatif des Arts et Manufactures" and of the "Direction des Études techniques," April, 1919, (Director: M. Guillet).

Sixty-five per cent of the French production was exported, half of which (i.e. 32 %) was sent directly or indirectly to Germany, approximately 15 % to Great Britain, and a certain proportion to the United States, which is rapidly falling off, as the new beds are developed in that country, in Tennessee and North Carolina.

Of the 7365 tons (7483 tonnes) of alumina exported, 80 % goes to supply the Swiss factories.

The Report of the French Minister of Commerce (loc. cit.) shows the influence of the war on the production of bauxite.

(a) *France.*

	Bauxite for Aluminium		Bauxite for other purposes		Total	
	Tonnes	Ton	Tonnes	Tons	Tonnes	Tons
1915	37,894	37,296	48,628	47,860	86,522	85,156
1916	68,866	67,779	37,334	36,743	106,200	104,520
1917	101,748	100,150	19,168	18,865	120,916	119,015

The diminution in production is clearly due to the large falling off of exports.

(b) *United States.*

1915 . .	293,253 tons	(297,961 tonnes)	of bauxite.
1916 . .	418,640 ,,	(425,359 ,,)	,,
1917 . .	559,750 ,,	(568,690 ,,)	,,

(c) *Great Britain.*

1915 . .	11,726 tons	(11,914 tonnes)	of bauxite.
1917 . .	14,714 ,,	(14,950 ,,)	,,

The whole of this amount was imported from the French beds at Var. The discovery of beds in British Guiana, where there are large waterfalls, will probably affect the British production very considerably.

(d) *Italy.*

Position unchanged.

(e) *Germany.*

Germany has been unable to import French bauxite, and has, therefore, since the war, begun to work the beds at Frankfort-on-Main.

(f) *Austria-Hungary.*

Austria-Hungary has supplied the needs of Germany during the war. Just when war was declared, very important beds

FIG. 3.—Map of South of France, to show distribution of Bauxite and situation of Alumina and Aluminium Works.

(20,000,000 tons) were discovered in Hungary (Siebenbergen). The bauxite was sent to Germany, and works were erected, on the spot, for treating the mineral. In addition, there are mines in Dalmatia, Herzegovina, Istria and Croatia, which are either being worked or are ready to be worked. The quality of this bauxite seems on the whole very inferior to that of the French.

II. Aluminium.

A statement of production figures can only be made with caution, discriminating between possible and actual output. The latter, a fraction of the former, depends upon the demand, and also upon the possibility of obtaining materials for the production of other substances—for instance, the manufacture of aluminium replacing that of chlorates, and conversely.

Statistics, from this point of view, are often lacking in clearness. Nevertheless, bearing in mind these two considerations, we can consider the following figures as sufficiently accurate, referring to an average annual production.

(a) *France.*

France, as is shown in the accompanying map (Fig. 3), is favourably situated for the production of aluminium. The close proximity of the bauxite beds, the alumina works, and the water power necessary for the electro-metallurgy, forms a unique combination, and, in addition, carbon can be easily conveyed to the works.

Actual output, 12,000–15,000 tons per annum.
Possible output, 18,000–20,000 tons per annum.

Aluminium Works.

The French works are amalgamated, forming " L'Aluminium française," and are grouped into companies :—

(i) The "Société Électro-métallurgique française," with works at Praz, and at St. Michel de Maurienne in the valley of the Arc, and at Argentière in the valley of the Durance.

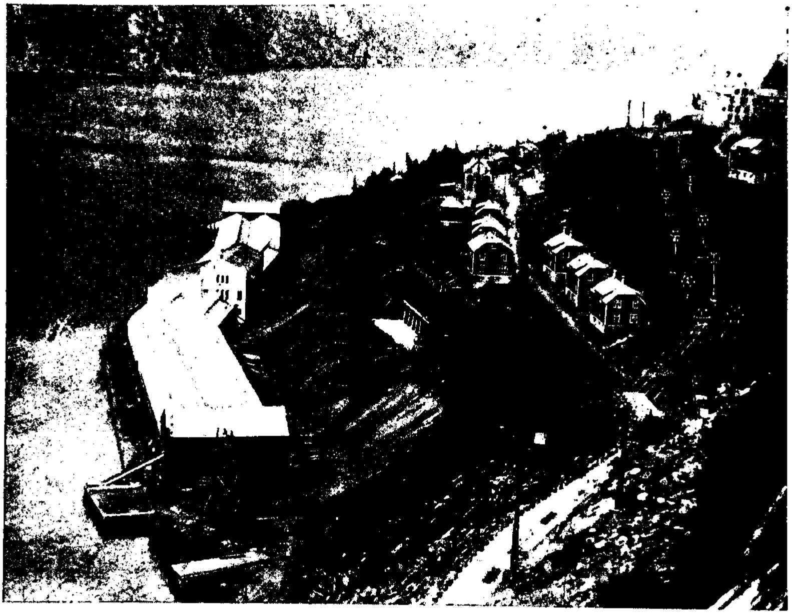
(ii) The " Compagnie des Produits chimiques d'Alais et de la Camargue," possessing the Calypso works (at St. Michel de Maurienne), and works at St. Jean de Maurienne in the valley of the Arc.

(iii) The "Société d'Électro-chimie," works at Prémont, in the valley of the Arc.

(iv) "La Société Électro-chimique des Pyrénées," with works at Auzat (Ariège).

PLATE I.

Photograph 1.—Norwegian Nitrides and Aluminium Company.
Works at Eydehavn near Arendal (25,000 h.p.), situated on an arm of the sea.



Photograph 2.—Norwegian Nitrides and Aluminium Company.
Works at Tyssedal (35,000 h.p.) on the Hardanger Fjord.

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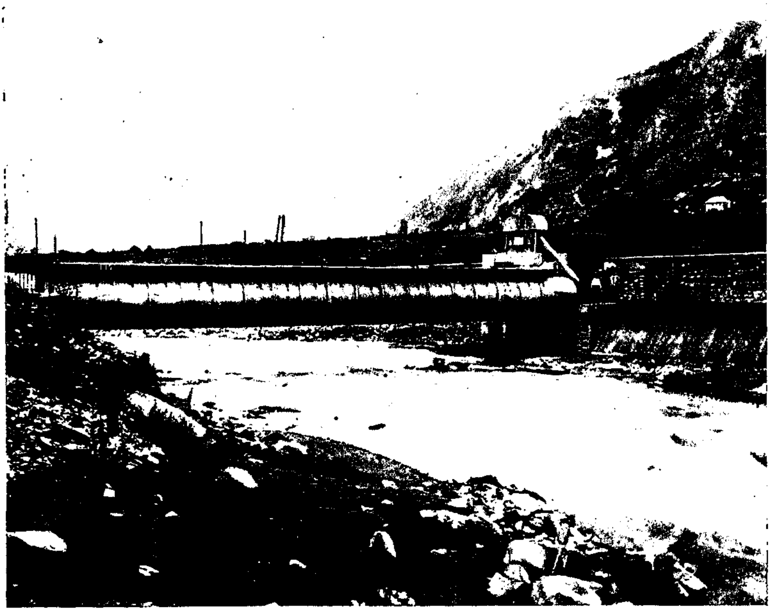
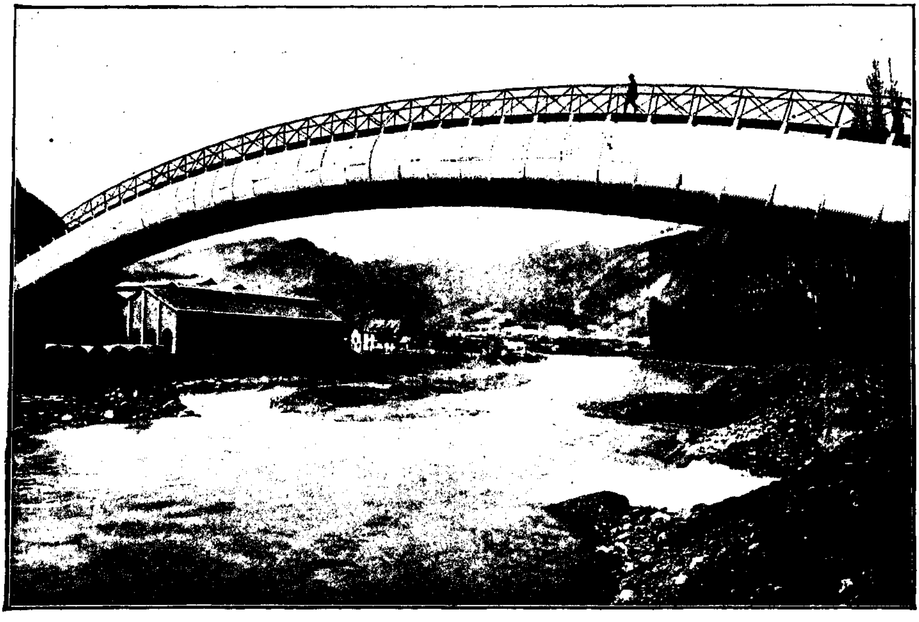
PLATE II.



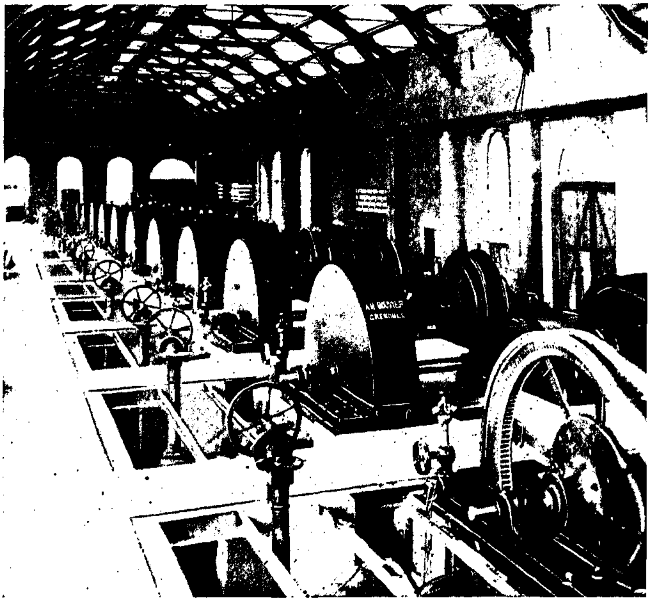
SAINT-JEAN—CYLINDRICAL DAM.



WORKS AT SAINT-JEAN—AQUEDUCT ACROSS THE ARC.

To face page 13

PLATE III.



ENGINE-ROOM AT CALYPSO.

To

ALUMINA WORKS.

The alumina works are situated near the bauxite beds in Hérault, Var, and Bouches-du-Rhône, at Gardanne and La Barasse (Bouches-du-Rhône) and at Salindres (Gard).

(b) *Great Britain.*

Output about 6000 tons.

There are two companies :—

(i) The British Aluminium Company (Scotland and Norway).

(ii) The Aluminium Corporation (works at Dolgarrog, North Wales).

(c) *Italy.*

Output 1500–2000 tons.

(d) *Switzerland.*

Output 12,000–13,000 tons, from works at Neuhausen (canton of Schaffhausen) and at Chippis and Martigny (canton of Valais). It is noticeable that in Switzerland there are no works for the preparation of alumina from bauxite, hence the materials required for the manufacture of aluminium, alumina and cryolite are imported.

(e) *Norway.*

The Norwegian output has been :—

1913 . .	approximately	1000 tons
1917 . .	,,	7000 ,,
1918 . .	,,	6000 ,,

Its possible production may be about 15,000–16,000 tons. Alumina is imported mainly from the works at Menessis (Somme) and Salzaete (Belgium), belonging to L'Aluminium française, which have been damaged during the war.

(f) *United States and Canada.*

The output of the United States and of Canada in recent years has been about 30,000 tons; it is capable of great development, but it is difficult to give precise details on the subject.

The "Rapport sur l'Industrie française" of the Minister of Commerce gives, as a probable figure for 1917, 70,000 tons, which might rise to 80,000 with further increasc in prospect.

The two large American companies are the Aluminium Company of America, and the Northern Aluminium Company

of Canada, having their main works at Niagara Falls, at Massena, at Quebec and at Schawinigan Falls respectively.

(g) *Germany and Austria.*

It is really difficult to give precise returns on the capacity for production of these two countries. It has been given as approximately 10,000 tons, though it is not possible actually to verify this figure.

In conclusion, the following table of actual world's production may be given, omitting all more or less hypothetical speculations :—

United States and Canada . .	70,000 tons	(?)
France	15,000 ,,	
Switzerland	12,000 ,,	
Great Britain	6,000 ,,	
Norway	6,000 ,,	
Italy	2,000 ,,	
Germany and Austria . . .	10,000 ,,	(?)
Total, about	120,000 tons	

PART II

PROPERTIES OF ALUMINIUM

CHAPTER I

PHYSICAL PROPERTIES

Density: 2·6 (as annealed), 2·7 (as worked, or when impurities (iron and copper) are present).

This places aluminium among the lightest metals (lead, 11·4; nickel, 8·94; iron, 7·8; tin, 7·3; zinc, 7; antimony, 6).

Atomic Weight: 26·9.

Specific Heat: 0·22, increasing with rise of temperature. It finally reaches 0·308 at about the melting point.

Thermal Conductivity: 36 (silver=100).

Aluminium is a substance, therefore, having a great specific heat, and a high thermal conductivity, which renders it particularly suitable for the manufacture of cooking utensils.

Electrical Conductivity and Resistance.

The electrical conductivity is very high, being about 60 % of that of copper. Its specific resistance is 2·78 microhms per centimetre cube.

Melting Point: about 650°.

CHAPTER II

ANALYSIS AND GRADING

THE division of aluminium into grades is based upon the amount of impurities present. The chief impurities are :—

Group I : Iron and silicon.

Group II : Carbides, sulphides, copper, zinc, tin, sodium, nitrogen, boron, titanium.

Group III : Alumina.

The electrodes, in particular the anodes, form the principal source of the impurities. The anodes can be made of petroleum coke, anthracite, or gas carbon, using tar as a binding material. All manufacturers prefer petroleum coke, which, before the war, contained 1 % of ash, and during the war, 2–3 %. The other materials, anthracite and gas carbon, contain 4–5 % of ash.

Group I : Iron and silicon.

The presence of more than 1 % of iron usually causes faulty castings which are useless. As a rule, the amount of silicon is about one-third of that of the iron, and rarely exceeds one-half.

Group II : Various impurities, other than alumina.

These impurities, with careful working, are present only in relatively small quantities, less than 1 %, but their estimation is necessary, since, owing to some accident during the working, they may attain abnormal proportions.

Group III : Alumina.

It is impossible to emphasise too much the importance of this impurity. For a long time, it was customary to estimate the iron, silicon and other impurities, and, ignoring the alumina, to determine the aluminium by difference. This method, in which alumina is returned as metallic aluminium, is unsatisfactory, for experience has shown that excessive

quantities of alumina are very harmful on account of its infusibility at casting temperatures,* its higher density,† and its insolubility in the molten metal.

This impurity must therefore be estimated. Furthermore, a high percentage of alumina seems to favour the formation of blow-holes. For these reasons, the melting up of aluminium scrap, more or less oxidised, gives poor results.

GRADES OF ALUMINIUM.

As already stated, the usual industrial practice is to estimate only iron and silicon, the aluminium content being determined by difference—this obviously gives a fictitious value.

Grade I: Aluminium nominally 99·5 %. i.e. the total amount of iron and silicon being equal to or less than 0·5 %.

Grade II: Aluminium nominally 99·0 %. i.e. the total amount of iron and silicon being equal to or less than 1·0 %.

Grade III: Aluminium nominally 98–99 %. i.e. the total amount of iron and silicon being equal to or less than 2 %.

Though retaining this long-established system of classification, the foregoing grading should be modified, so as to take into account the impurities of the second group as well as those of the first, still, however, ignoring the alumina.

We then have the following grades :—‡

Grade I: Aluminium content (by difference) 99·5 % or over.

Grade II: Aluminium 99–99·5 %.

Grade III: Aluminium 98–99 %.

In the first two grades, the impurities of the second group (carbides, sulphides, copper, zinc, tin, sodium, nitrogen, boron, and titanium) should not exceed 0·3 %; in the third grade these impurities should not exceed 0·4 %, the iron 1 %, and the silicon 0·6 %.

Alumina is not considered in calculating the purity, but should not exceed 0·4 % for Grade I, 0·6 % for Grade II, and 0·8 % for Grade III. These are safe limits to allow, without interfering with, or reducing, the production.

* Melting point of alumina 3,000° C., of aluminium 650° C.

† Density of alumina 3·75, of aluminium 2·6.

‡ This system of grading is adopted in the French Aeronautical Specifications, and the analytical methods are given in Appendix I. A variation of 0·25 % in the aluminium content is allowed in Grade I, 0·50 % in Grade II, and 0·75 % in Grade III.

CHAPTER III

MECHANICAL PROPERTIES

THE mechanical properties can be grouped as follows :—

A. *Tensile Properties:* Tensile Strength, Elastic Limit, and Elongation.

B. *Hardness and Shock Resistance.*

C. *Cupping Value:* Depth of Impression and Breaking Load.

Tests have been carried out on metal of varying thickness, as shown below :—

0·5 mm. sheet : Tensile and Cupping Tests.
2 mm. sheet : Tensile, Cupping, and Hardness (scleroscope) Tests.
10 mm. sheet : Tensile, Shock, and Hardness Tests.

The variations in these properties with

(i) different amounts of cold work ;

(ii) different anneals subsequent to varying degrees of work, have been investigated. An account of the experiments and results will be given in the following form :—

A. TENSILE PROPERTIES.

(i) Variation in tensile properties with the amount of cold work.

(*a*) Thin test pieces.
(*b*) Thick test pieces.

Discussion of Results.

(ii) Variation in tensile properties with increasing annealing temperature, following varying amounts of cold work.

(*a*) Thin test pieces.
(*b*) Thick test pieces.

Discussion of results.

B. HARDNESS AND SHOCK RESISTANCE.

(i) Variation of these properties (Brinell Hardness and Shock Resistance) with amount of cold work, using test pieces

of 10 mm. thick sheet, and variation of Scleroscope Hardness with the amount of cold work for sheets of the thin series.

Discussion of results.

(ii) Variation of Brinell Hardness and Shock Resistance with increasing annealing temperature, after varying amounts of cold work, using test pieces from sheets 10 mm. thick (thick series).

Discussion of results.

C. Cupping Value.

Depth of impression and breaking load, using test pieces of metal comprising the thin series only.

(i) Variation of these properties with amount of cold work.

(ii) Variation of these properties with increasing annealing temperature following varying amounts of cold work.

Discussion of results.

D. Final Summary.

E. Contemporary Literature on the Subject.

A. Tensile Properties

Thin Series

Dimensions of test pieces.

Type Ia.

Between shoulders { Length 100 mm. / Breadth 20 mm. / Thickness 0·5 mm. }

Area of cross section 10 sq. mm.*

Gauge length (for measuring elongation) $=\sqrt{66\cdot67s}$ $=30$ mm.

Type Ib.

Between shoulders { Length 100 mm. / Breadth 20 mm. / Thickness 1 mm. }

Area of cross section 20 sq. mm.

Gauge length $=\sqrt{66\cdot67s}=36$ mm.

Type Ic.

Between shoulders { Length 100 mm. / Breadth 20 mm. / Thickness 1·5 mm. }

Area of cross section 30 sq. mm.

Gauge length $=\sqrt{66\cdot67s}=45$ mm.

* These values are only approximate. In each case the breadth and thickness were measured to the nearest ·01 mm., and the exact cross section calculated from these figures.

TYPE ID.

Between shoulders { Length 100 mm. Breadth 20 mm. Thickness 2 mm.

Area of cross section 40 sq. mm.
Gauge length $= \sqrt{66 \cdot 67 s} = 50$ mm.

Thick Series

TYPE II.

Between shoulders { Length 100 mm. Breadth 15 mm. Thickness 10 mm.

Area of cross section 150 sq. mm.
Gauge length $= \sqrt{66 \cdot 67 s} = 100$ mm.

TESTING LABORATORIES.

The experiments on the variation of mechanical properties with cold work (thin series) and the cupping tests (both in the worked and annealed states) were carried out at the "Chalais Meudon" Laboratory. The experiments on the effect of annealing at different temperatures after cold work were carried out at the Conservatoire des Arts et Métiers. Reports of the latter experiments are given in the appendices.

I. *Variation of the Tensile Properties (Tensile Strength, Elastic Limit, and Elongation) with the amount of cold work.*

DEFINITION OF COLD WORK.

A metal, which, as the result of work "in the cold," i.e. at relatively low temperatures, has undergone permanent deformation, is said to be "cold worked" or "work hardened." The properties of the metal, thus treated, are changed, and the amount of this change is a measure of the cause—the so-called cold work. A metal which has been completely annealed has, by definition, zero cold-work.

If S be the initial section of a bar in the annealed state and if s be the final section after cold work (drawing or rolling), the cold work may be defined in terms of the deformation as follows :—

$$\text{Cold work } (\%) = \frac{S(\text{initial}) - s(\text{final})}{s(\text{final})} \times 100.$$

As has been pointed out in the author's work on "Copper and Cartridge Brass," the "percentage cold work" given by the above formula is a function of the deformation only, and does not give any indication of the value of the mechanical

properties. The latter may actually remain stationary, while the percentage of deformation continues to increase with the deformation itself. We can therefore distinguish two values :—

(*a*) The cold work in terms of deformation (theoretical cold work).

(*b*) The cold work in terms of the change in mechanical properties (effective cold work).

In this book, unless otherwise stated, it is always the former that is meant, and this allows of easy evaluation in course of manufacture.

(a) *Thin Series*

The tests on the thin series were carried out on test pieces cut respectively from sheets of the thicknesses specified :—

Type I*a*	. .	Thickness 0·5 mm.
,, I*b*	. .	,, 1·0 mm.
,, I*c*	. .	,, 1·5 mm.
,, I*d*	. .	,, 2·0 mm.

Sheets of each of the above thicknesses were subjected to the following amounts of cold work, and the results investigated.

Cold work 0 %	Ratio S/s 0	(completely annealed)
,, 50 %	,, 1·5	
,, 100 %	,, 2	
,, 300 %	,, 4	

Method of working sheets and slabs so as to obtain required amounts of cold work.

Two methods were employed in the preliminary working of the sheets and slabs.

First Method.

Annealed Metal. A slab 40 mm. thick at an initial temperature of 450° is reduced to the required thickness by hot rolling, without intermediate reheating, and is finally annealed at 350°.

Cold-Worked Metal. Assuming that 100 % cold work is desired, a sheet 40 mm. thick is reduced by hot rolling, without intermediate reheating, to double the final thickness required. It is then annealed at 350°, and cold rolled so as to reduce the section by one-half. A similar process is employed for the other degrees of cold work investigated.

SECOND METHOD.

A slab 40 mm. thick, at an initial temperature of 450°, is reduced to a uniform thickness of 8 mm. by hot rolling.

Annealed Metal. The sheet, 8 mm. thick, is reduced to the required thickness by cold rolling, with intermediate annealing at 350° every 2 mm. reduction, and is finally annealed at 350°.

Cold-Worked Metal. Assuming that 100 % cold work is desired, the sheet, 8 mm. thick, is reduced by cold rolling, with intermediate annealing every 2 mm. reduction, to double the final thickness required. It is then annealed at 350°, and cold rolled so as to reduce the section by one-half. A similar process is employed for the other degrees of cold work investigated.

A comparative study of the cold working of thin sheets was carried out by both these methods, whereas in the study of the cold working of thick sheets, and in the study of annealing alone, the second method only was employed. Although the second method is more uniform and more sound, it has not given results superior to those of the first.

As will be seen below, it seems as if, up to a certain limit, large amounts of cold work need not be avoided in manufacture, provided that this is only an intermediate stage, and is followed by a re-softening anneal.

ANALYSIS

	Cold work 0 %			
Thickness	0·5 mm.	1 mm.	1·5 mm.	2 mm.
Iron	0·93 %	0·82 %	0·98 %	0·95 %
Silicon	0·56	0·52	0·56	0·45
	Cold work 50 %			
Iron	0·88	0·84	0·97	0·93
Silicon	0·25	0·26	0·39	0·41
Alumina	0·36	0·30	0·26	0·34
	Cold work 100 %			
Iron	0·81	0·83	0·70	0·81
Silicon	0·32	0·38	0·23	0·23
Alumina	0·24	0·29	0·26	0·24
	Cold work 300 %			
Iron	0·88	0·77	0·85	0·72
Silicon	0·31	0·46	0·56	0·46
Alumina	0·17	0·16	0·24	0·22

NUMBER OF TESTS.

For each degree of cold work, two sheets were used for the tensile tests, and in each sheet three test pieces were cut longitudinally and three transversely.

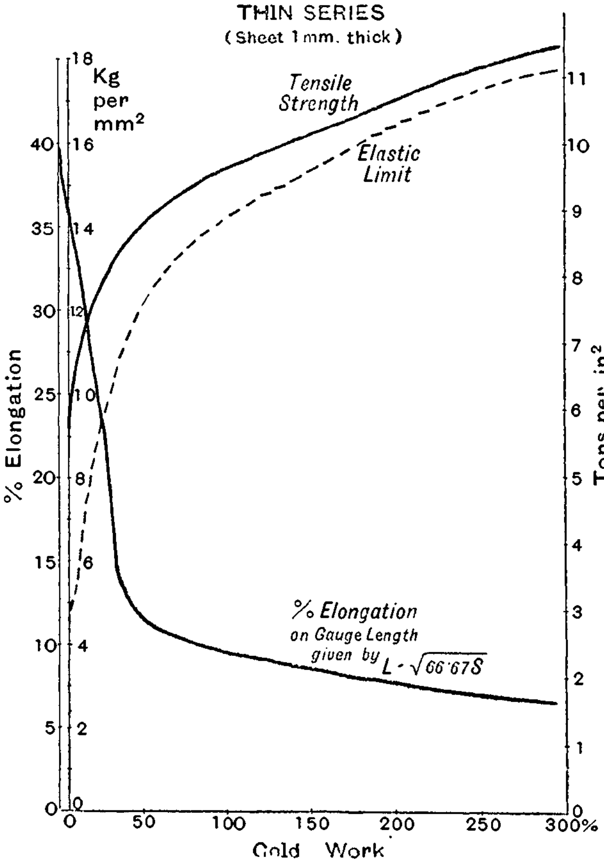


FIG. 4.—Variation in Mechanical (tensile) Properties with Cold Work.

RESULTS OF TESTS.

Fig. 4 summarises the results for test pieces of the Type I*b* (1 mm. thickness) cut longitudinally.

After discussing the results obtained for this type, we will point out the variations observed, due to the different thicknesses of the sheets comprising the thin series, and to the

direction, longitudinal or transverse, in which the test pieces were cut.

Cold work 0 % (annealed state):—

Elastic Limit: 4·5 kg. per sq. mm. (2·86 tons per sq. in.).
Tensile Strength: 9·0 kg. per sq. mm. (5·72 tons per sq. in.).
Elongation: 40 %.

Cold work 50 %:—

Elastic Limit: 12·0 kg. per sq. mm. (7·62 tons per sq. in.).
Tensile Strength: 14·0 kg. per sq. mm. (9·09 tons per sq. in.)
Elongation: 11 %.

Cold work 100 %:—

Elastic Limit: 14·0 kg. per sq. mm. (8·89 tons per sq. in.).
Tensile Strength: 15·0 kg. per sq. mm. (9·52 tons per sq. in.)
Elongation: 9 %.

Cold work 300 %:—

Elastic Limit: 17·5 kg. per sq. mm. (11·11 tons per sq. in.).
Tensile Strength: 18·0 kg. per sq. mm. (11·43 tons per sq. in.).
Elongation: 6 %.

(i) Merely cold working to the extent of 50 % has completely changed the properties of aluminium, and the Elongation has been reduced to a quarter of its original value. Consequently, if work hardening is undesirable, even a very small amount of deformation must be avoided, since the changes in the properties take place very markedly from the outset.

(ii) The maximum cold work, beyond which deterioration and disintegration may set in, is reached when the Tensile Strength is approximately doubled.

(iii) If cold work be expressed, no longer in terms of the deformation, but in terms of the changes in the properties, then, choosing as variable the Tensile Strength, and employing the formula

$$\text{Cold work} = \frac{R - r}{r}$$

where R = Tensile Strength (cold worked)
r = Tensile Strength (annealed)

we have, in the case of the thin series, the following results:—

Cold work (deformation)		0 %	Cold work (effective)		0
,,	,,	50 %	,,	,,	$\frac{1}{3}$
,,	,,	100 %	,,	,,	$\frac{2}{3}$
,,	,,	300 %	,,	,,	1

It seems, therefore, that 200–300 % cold work is the maximum for the working of aluminium, giving what might be called the "Maximum Effective Cold Work."

INFLUENCE OF THICKNESS (THIN SERIES).

The variation in thickness between 0·5 mm. and 2·0 mm. exerts only a slight effect on the results, so that the mean curve given for test pieces of 1·mm. thickness may be taken as the curve for all the thin series.

EFFECT ON TENSILE PROPERTIES OF THE DIRECTION IN WHICH TEST PIECES WERE CUT.

The Elongation in the transverse test pieces is less than that in the longitudinal.

Cold work 0 %	Difference 10 %
Cold work 50 % and above	Maximum difference 40 %

In the Tensile Strength and Elastic Limit there is practically no difference.

(b) *Thick Series*

The tests on the "Thick Series" have been carried out on test pieces of Type II, thickness 10 mm., cut from sheets of this thickness.

The following different amounts of cold work were investigated :—

Cold work 0 %	Ratio : $\frac{\text{Initial Section}}{\text{Final Section}} = 0$	(completely annealed)
,, 50 %	,, 1·5	
,, 100 %	,, 2	
,, 300 %	,, 4	

ANALYSIS.

Cold work 0 % :—

Aluminium	99·00 %
Iron	0·64 %
Silicon	0·33 %
Carbon	0·03 %
Alumina	traces.

Cold work 50 % :—

Aluminium	98·80 %
Iron	0·72 %
Silicon	0·35 %
Carbon	0·08 %
Alumina	traces.

Cold work 100 % :—

Aluminium	98·60 %
Iron	0·84 %
Silicon	0·41 %
Carbon	0·07 %
Alumina	traces.

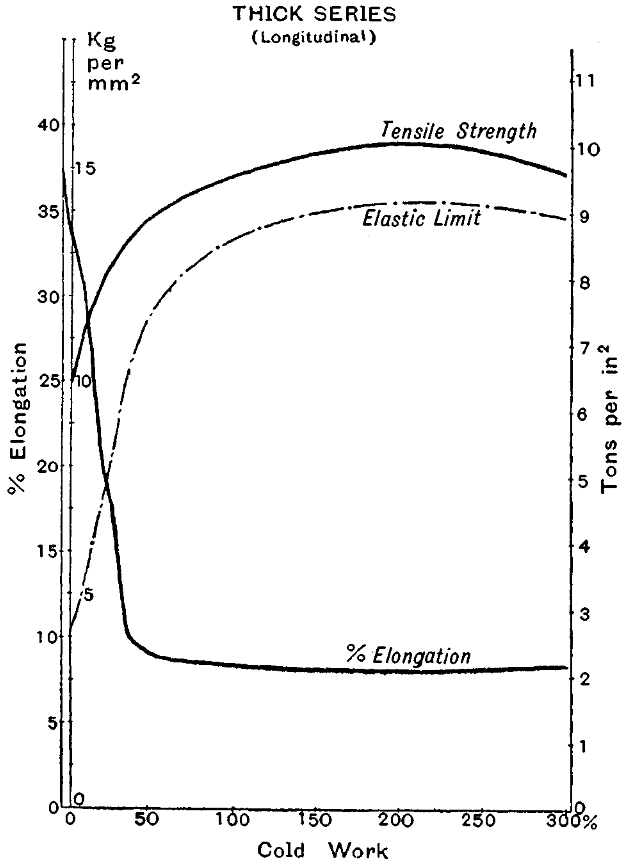


Fig 5.—Variation in Mechanical Properties with Cold Work.

Cold work 300 % :—

Aluminium	99·01 %
Iron	0·61 %
Silicon	0·33 %
Carbon	0·03 %
Alumina	traces.

Figs. 5 and 6 summarise the variations in properties in the case of the thick series (sheets 10 mm. thick).*

FIG. 5. TESTS ON LONGITUDINAL TEST PIECES.

As can be seen, the variations in the properties with cold work (deformation) are similar to those of the thin series.

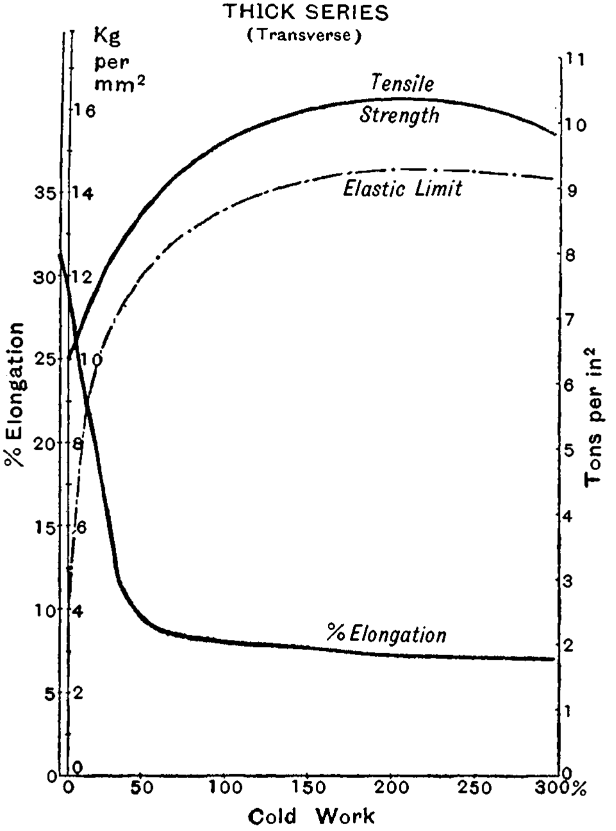


FIG. 6.—Variation in Mechanical Properties with Cold Work.

In every case the minima and maxima are approximately the same.

Tensile Strength. Minimum, 10 kg. per sq. mm. (6·35 tons per sq. in.).
Maximum, 16 kg. per sq. mm. (10·16 tons per sq. in.).

* Cf. Appendix III. Report of the Conservatoire des Arts et Métiers. No. 13456, February 5th, 1919.

Elongation. Minimum, 8 %. Maximum, 38 %.

In the case of aluminium in thin sheets as compared with thick,

(i) The cold work, whatever its amount, is more homogeneous throughout the thickness.

(ii) The effect of annealing is more complete.

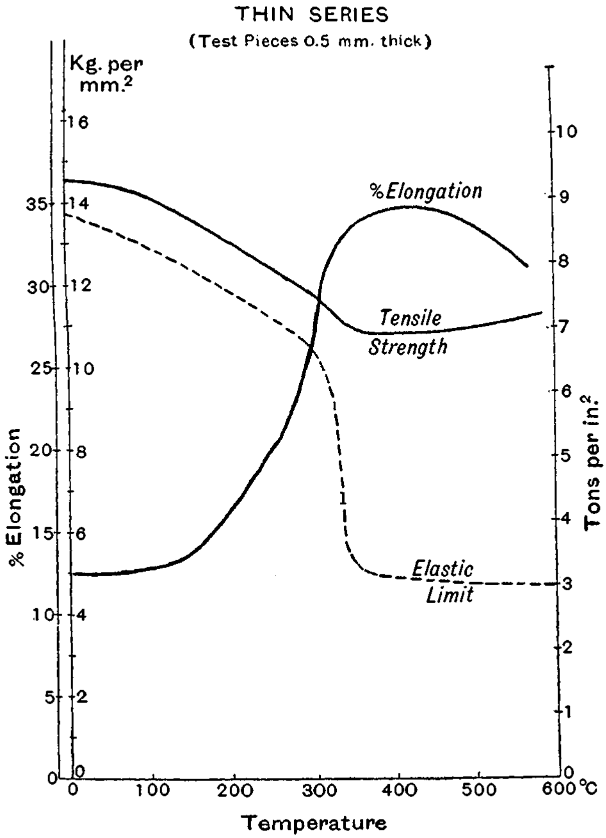


FIG. 7.—Variation in Mechanical Properties on Annealing at different Temperatures after 50 % Cold Work.

FIG. 6. TESTS ON TRANSVERSE TEST PIECES.

The Tensile Strength and Elastic Limit are little affected by the direction in which the test pieces are cut, but, on the other hand, the Elongation undergoes variations of the order of 15 to 20 %.

II. *Variation of Tensile Properties with increasing Annealing Temperature following varying amounts of Cold Work.*

(a) *Thin Series*

EXPERIMENTAL DETAILS OF THE TESTS.

The tests were carried out on two series of tensile test pieces from sheets of aluminium, the one 0·5 mm. thick, Type I*a*,

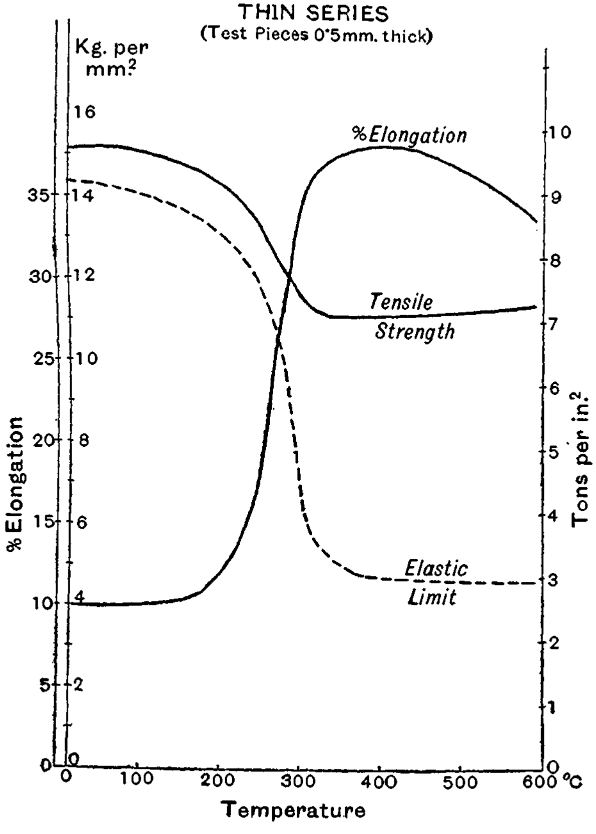


FIG. 8.—Variation in Mechanical Properties on Annealing at different Temperatures after 100 % Cold Work.

the other, 2·0 mm. thick, Type I*d*. Each of these series includes metal in three degrees of cold work, 50, 100, and 300 %.

INVESTIGATION OF THE DURATION OF TIME NECESSARY FOR COMPLETE ANNEAL AT VARIOUS TEMPERATURES.

Preliminary tests have been carried out with a view to determining the minimum time necessary to give the properties characterising each temperature.*

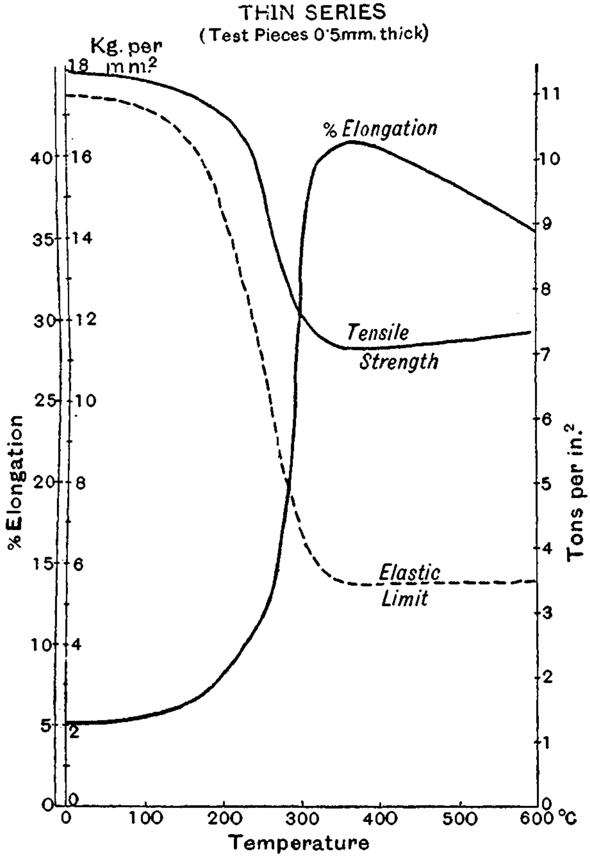


FIG. 9.—Variation in Mechanical Properties on Annealing at different Temperatures after 300 % Cold Work.

The following results were obtained for the two series :—

Bath	*Temperature*	*Duration of Time*
Oil	100°—150°—200°—250°—300°	5 minutes.
Sodium nitrite .	350°—400°—450°—500°	3 minutes.
Potassium nitrate .	550°—600°	1 minute.

* Cf. Appendix IV. Report of the Conservatoire des Arts et Métiers. No. 13357, January 24th, 1919.

TEST PIECES 0·5 mm. THICK. TYPE 1A.

Figs. 7, 8, and 9 summarise the results obtained.

STAGES OF ANNEALING.

Whatever the amount of work, the following stages can be distinguished :—

(i) Region of cold work.
(ii) Region of softening.
(iii) Region of complete anneal.
(iv) Region of falling-off of Elongation.

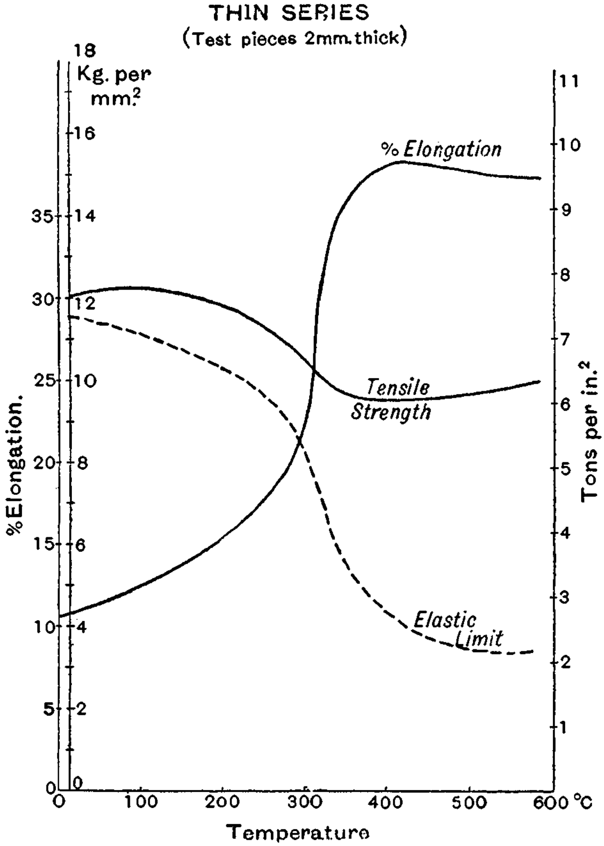


FIG. 10.—Variation in Mechanical Properties on Annealing after 50 % Cold Work.

(i) *Region of Cold Work ;* 0–150°.

Within this range, the properties remain similar to those which the metal possesses in the particular cold-worked state,

as given in Fig. 4. The effect of temperatures up to 150° is therefore insignificant.

(ii) *Region of Softening;* 150–350°.

This is a transition stage, in which the aluminium becomes softer, and gradually acquires the properties of completely annealed metal.

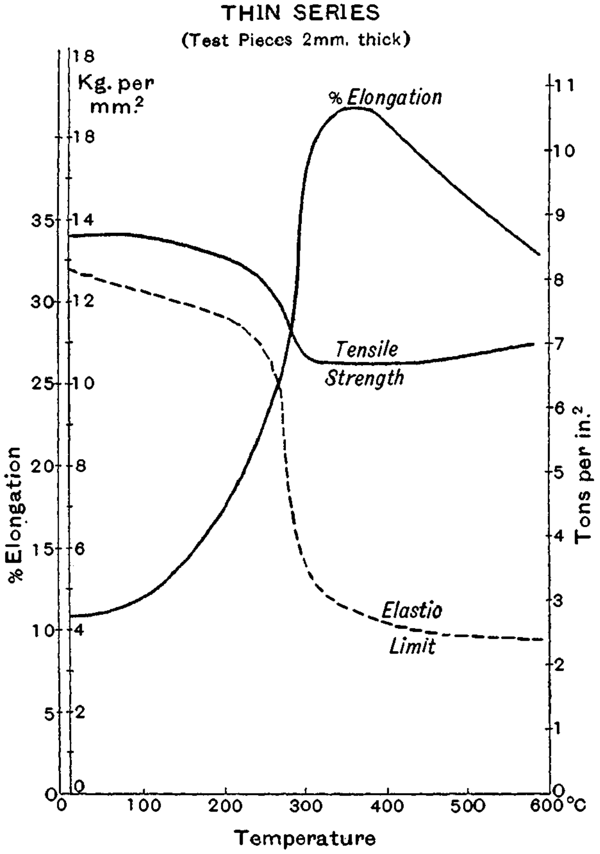


FIG. 11.—Variation in Mechanical Properties on Annealing after 100 % Cold Work.

(iii) *Region of Complete Anneal;* 350–450°.

This is the region in which the extent of anneal remains approximately constant ; that is to say, in which the properties of the metal are almost the same after annealing at any temperature within this range.

350° to 450° is, therefore, the optimum annealing range of temperature.

(iv) *Region of Falling-off of Elongation;* 450–500°.

In this region there is a decrease in the Elongation, without any appreciable change in the Tensile Strength and Elastic Limit.

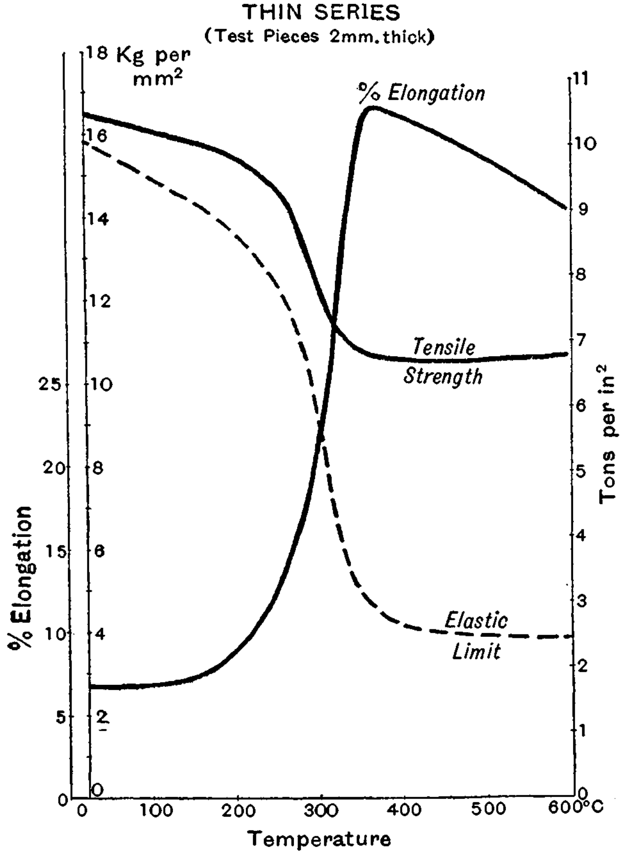


FIG. 12.—Variation in Mechanical Properties on Annealing after 300 % Cold Work.

NOTES ON THE RESULTS.

(i) The softening is the more abrupt as the original cold work increases.

(ii) The temperature of complete anneal (characterised by maximum elongation) becomes lower as the cold work increases.

Amount of Original Cold Work	*Temperature of Maximum Elongation*
50 %	425°
100 %	400°
300 %	350°

(iii) The values of the properties in the completely annealed state increase with the amount of original cold work, up to 300 %.

Amount of Cold Work	Tensile Strength		Elastic Limit		% Elongation
	Kg./mm.²	Tons/in.²	Kg./mm.²	Tons/in.²	
50 %	10·8	6·86	4·8	3·05	34·0
100 %	11·0	6·99	4·5	2·86	37·5
300 %	11·2	7·11	5·2	3·31	40·0

This shows that, in the treatment of aluminium, it is advisable to employ extensive cold work, up to a maximum amount varying between 200 % and 300 %, always provided that the work is followed by an anneal adequate in duration and at a suitable temperature.

Large amounts of cold work—

(i) lower the length of time necessary for complete anneal,
(ii) lower the temperature of complete anneal,
(iii) improve the properties.

TEST PIECES 2 mm. THICK. TYPE ID.

Figs. 10, 11, and 12 summarise the results. The same regions are noticeable as in Figs. 7, 8, and 9, and lie, approximately, within the same limits of temperature, and the same remarks may be made as to the results obtained after varying cold work.

(b) *Thick Series*

EXPERIMENTAL DETAILS OF TESTS.

Tests were carried out on test pieces (Type No. II, 10 mm. thick) taken from sheets of that thickness having been cold worked to the extent of 100 and 300 %.

INVESTIGATION OF THE DURATION OF TIME NECESSARY FOR COMPLETE ANNEAL AT VARIOUS TEMPERATURES.

As in the case of the thin test pieces, preliminary tests were carried out with a view to determining the time required to give the properties characterising each temperature.*

* Cf. Appendix V. Report of the Conservatoire des Arts et Métiers. No. 13463.

The results are as follows :—

Bath	*Temperature*	*Duration of Time*
Oil	100–125–150–175–200–225–250°	6 minutes.
Sodium nitrite . .	275–300–325–350–375–400–425–450°	4 ,,
Potassium nitrate .	475–500–525–550–575–600°	2 ,,

Figs. 13 and 14 summarise the variations in mechanical properties for the thick series (sheets 10 mm. thick).

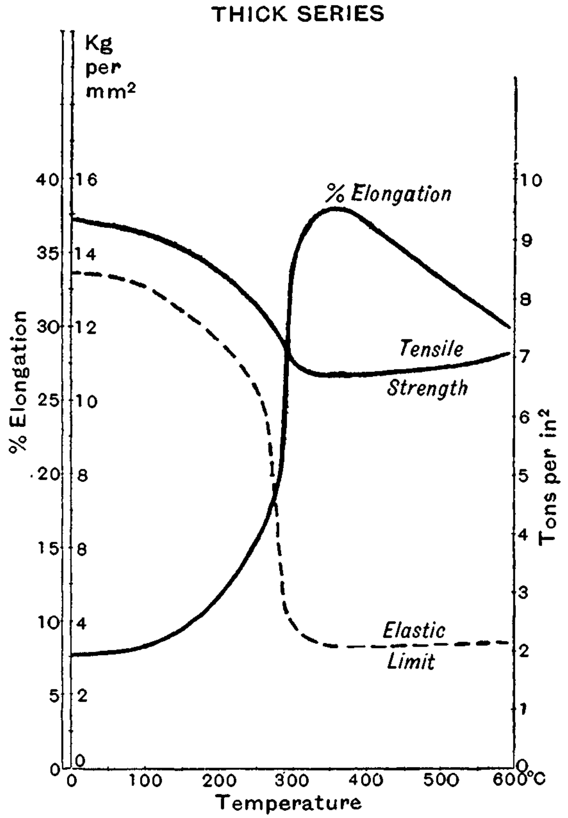


Fig. 13.—Variation in Mechanical Properties on Annealing after 100 % Cold Work.

Figs. 13 (100 % Cold Work) and 14 (300 % Cold Work).

As in the case of the thin series, the same regions are noticeable, and a comparison of the two figures leads to the same conclusions as to the effect of initial cold work on the results obtained after a subsequent anneal.

B. Hardness and Shock Resistance

I. *Variation of the Brinell Hardness and Shock Resistance with the amount of cold work, using test pieces taken from sheets* 10 *mm. thick, and of the Shore scleroscope hardness, with the amount of cold work, for sheets of the thin series.*

Hardness Tests.

(a) *Brinell Tests on thick sheets.*

These were carried out under a load of 500 kg. and 1000 kg. respectively, using a ball 10 mm. in diameter. The results are shown in Fig. 15.

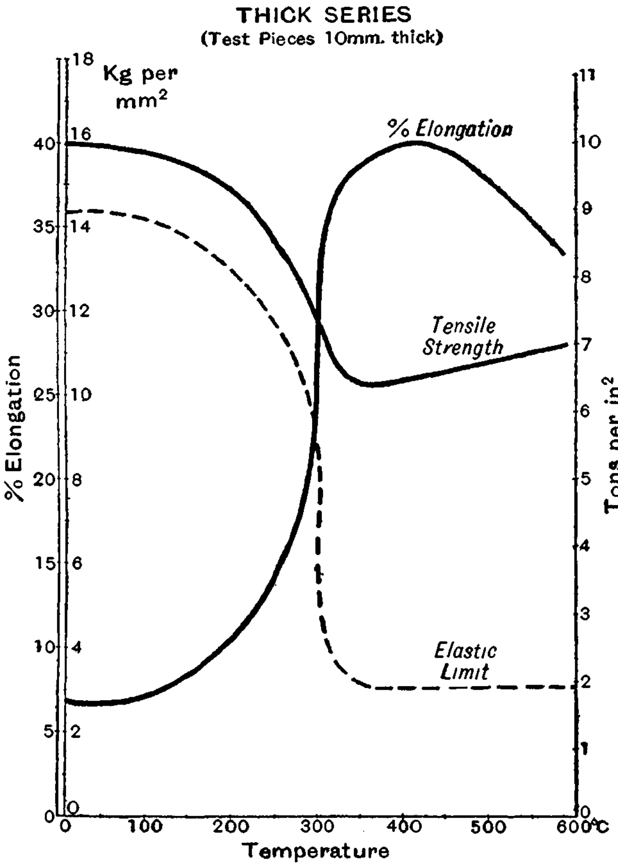


Fig. 14.—Variation in Mechanical Properties on Annealing after 300 % Cold Work.

As is evident from a comparison of Fig. 15 and Fig. 5, the curves of Tensile Strength and Elastic Limit plotted against cold work are of the same general form as the hardness curves

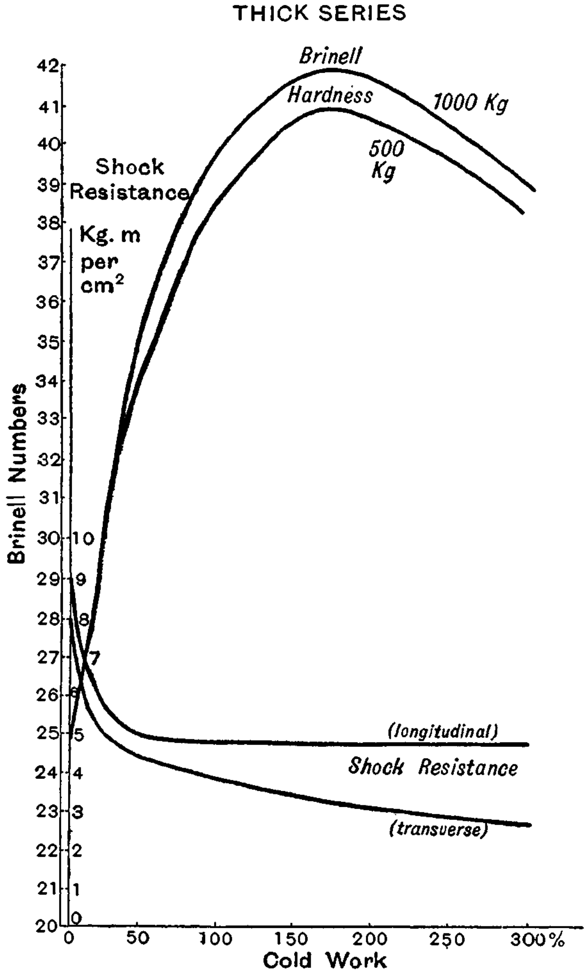


Fig. 15.—Variation in Mechanical Properties (Hardness and Shock) with Cold Work.

under 500 kg. and 1000 kg. These hardness curves under 500 and 1000 kg. deviate very little from each other, and the divergences, for which experimental errors are partly responsible, need no comment.

Annealed aluminium possesses a Brinell Hardness of 23 under 500 or 1000 kg., corresponding with a Tensile Strength of approximately 10 kg. per sq. mm. (6·35 tons per sq. in.). In the case of the thick series, the maximum hardness, as also the maximum Tensile Strength, occurs at 200 % cold work.

(b) *Shore Scleroscope Tests on thin sheets.*

As ball tests are impossible on thin sheet, rebound tests were made, using the Shore apparatus, on sheets of the thin series, possessing respectively 50 %, 100 %, and 300 % cold work.

The average scleroscope numbers of sheets 1 and 2 mm. thick are as follows :—

	Average scleroscope number	
	Test pieces 1 mm. thick	2 mm. thick
As annealed . .	4·5	5·5
50 % cold work .	16·0	11·5
100 % cold work .	24·0	14·0
300 % cold work .	28·0	16·0

The scleroscope numbers vary with the thickness, but, whatever the thickness, the scleroscope number of completely annealed metal varies between 4 and 6, providing, therefore, a convenient means of verifying the extent of anneal.

Shock Tests.

These were carried out on test bars, 55×10×10 mm., with a Mesnager notch of 2 mm. depth, using a 30 kg. m. charpy pendulum of the Conservatoire des Arts et Métiers.

The results are also shown in Fig. 15. If the Shock Resistance curves (longitudinal and transverse) of Fig. 15 be compared with the Elongation curves of Figs. 5 and 6, it will be seen that they are of identical shape.

At 50 % cold work, the Shock Resistance reaches almost its minimum value. In the annealed state, the Shock Resistance varies between 8 and 8·5 kilogramme-metres per sq. cm., without any appreciable difference between test pieces cut longitudinally or transversely. This difference, however, becomes more marked as the cold work increases.

Minimum Shock Resistance, 300 % cold work (longitudinal) 5 kg. m. per sq. cm.

Minimum Shock Resistance, 300 % cold work (transverse) 3 kg. m. per sq. cm.

II. *Variation of Brinell Hardness and Shock Resistance with increasing annealing temperature after varying amounts of cold work, using test pieces taken from sheets* 10 *mm. thick.*

Figs. 16 and 17, corresponding with 100 % and 300 % cold work respectively, summarise the results.

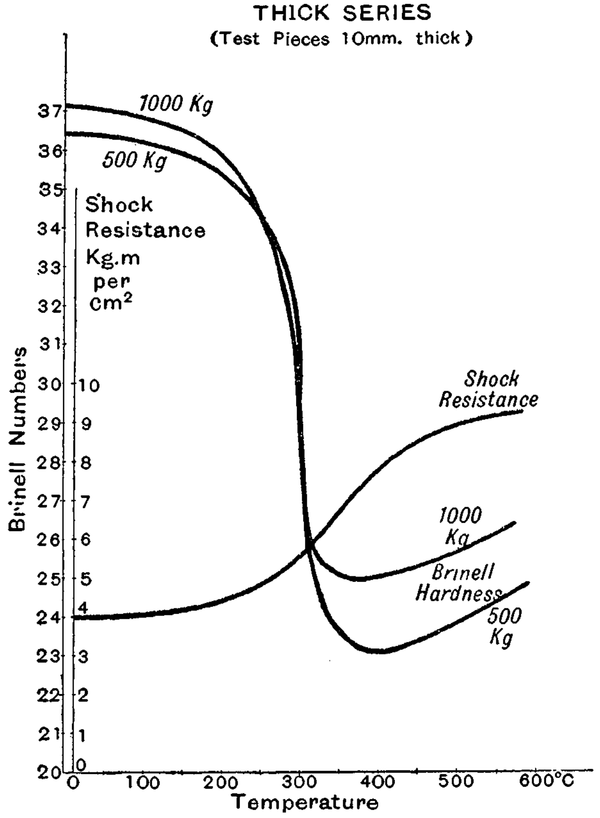


FIG. 16.—Variation in Mechanical Properties (Hardness and Shock) on Annealing after 100 % Cold Work.

HARDNESS.

The hardness curves under 1000 kg. and 500 kg. are shown in the figures. These curves diverge little ; they are practically identical in the region of cold work, and diverge chiefly in the region of anneal, where the hardness under 1000 kg. is slightly greater than that under 500 kg. The object in obtaining

these curves is not so much to compare the actual hardness numbers under 500 and 1000 kg., as to gain some indication of the trend of these values under two different loads. The advantage of this is evident; for instance, in the case of high temperature tests, where the determination of hardness under

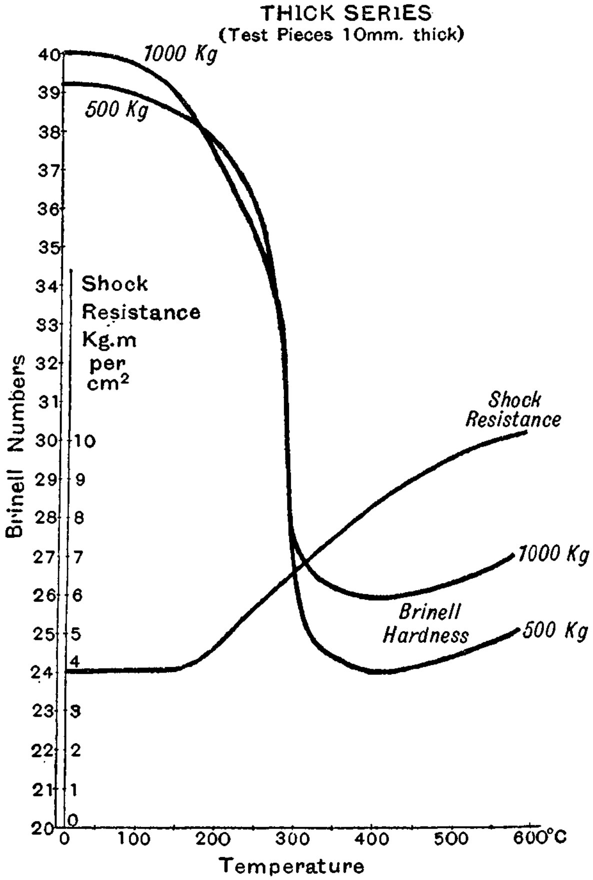


FIG. 17.—Variation in Mechanical Properties (Hardness and Shock) on Annealing after 300 % Cold Work.

1000 kg. would not be possible, the hardness must be determined under 500 kg. Since we have all the necessary data, we may then extend our results, and make such deductions as are useful.

It is evident from Figs. 16 and 17 that the hardness curves exhibit the same regions as the curves for the Tensile properties, as noted above.

SHOCK RESISTANCE.

It should be observed that in the cold-work region (0°–150° c.) the Shock Resistance remains approximately constant, having a value of about 4 kg. m. per sq. cm. for 300 % cold work. It rises gradually in the softening region, and in the completely annealed zone it reaches 8 kg. m. per sq. cm. on annealing at 400° c. after 100 and 300 % cold work. It continues to increase slowly up to 9 kg.m. per sq. cm. on annealing at 600° after 100 % cold work, and even to 10 kg. m. per sq. cm. on annealing at this temperature after 300 % cold work.

C. CUPPING TESTS

Depth of Impression and Breaking Load

EXPERIMENTAL DETAILS.

Cupping tests were carried out on sheet metal by means of the Persoz apparatus (Fig. 18) in the Chalais laboratory.

This apparatus consists, essentially, of a graduated rod furnished at one end with a plate and at the other with a ball 20 mm. in diameter. This ball rests on a circle 90 mm. in diameter taken from the sheet to be tested and gripped between two serrated annular rings of 50 mm. internal diameter.

By subjecting the whole apparatus to a compressional stress between the two plates of a testing machine, steadily increasing pressures can be applied to the centre of the circle, through the ball. This compression is continued right up to the point of rupture of the dome which forms, in the sheet, under the pressure of the ball.

The breaking load, and the depth of the impression made in the sheet, at the point of rupture, can thus be measured. The apparatus permits the measurement of the depth of impression with a maximum error of ·02 to ·03 mm.

I. *Variation of Depth of Impression and Breaking Load with the amount of Cold Work.*

Figs. 19 and 20 summarise the results. The values depend upon two variables :—

(i) The percentage of cold work.
(ii) The thickness of the sheets.

The degrees of cold work investigated were 0 % (annealed), 50 %, 100 %, and 300 %, and the sheets, on which tests were

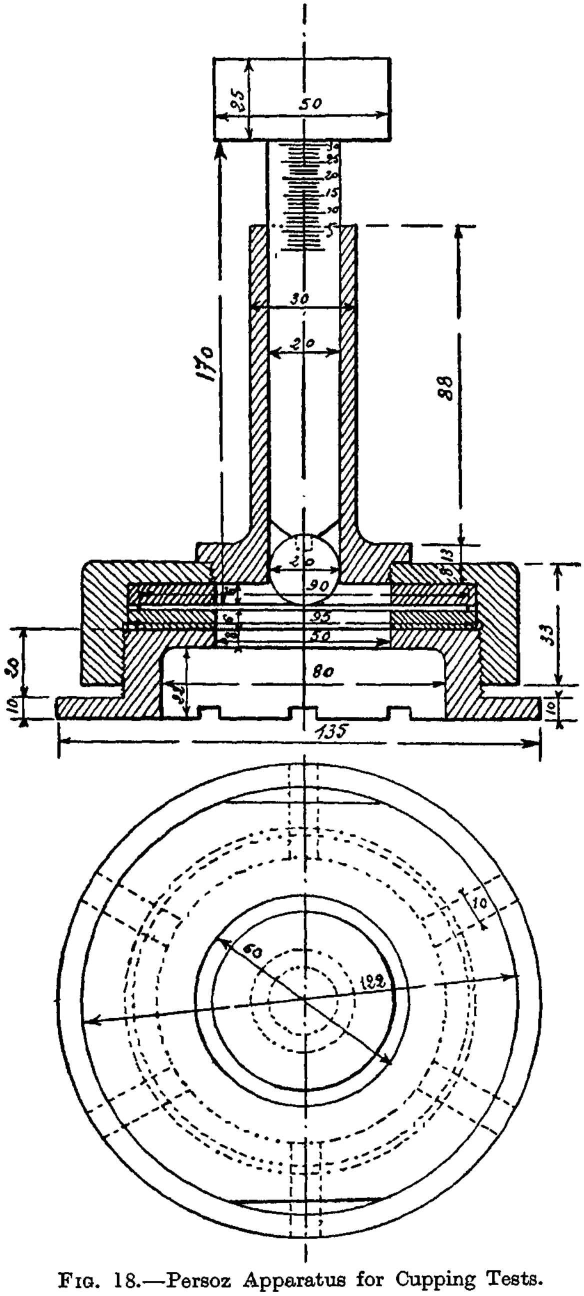


Fig. 18.—Persoz Apparatus for Cupping Tests.

carried out, were those comprising the thin series ; 0·5 mm., 1·0 mm., 1·5 mm., and 2·0 mm. in thickness respectively.

Fig. 19 shows for each thickness the variation of the Depth of Impression and Breaking Load with cold work.

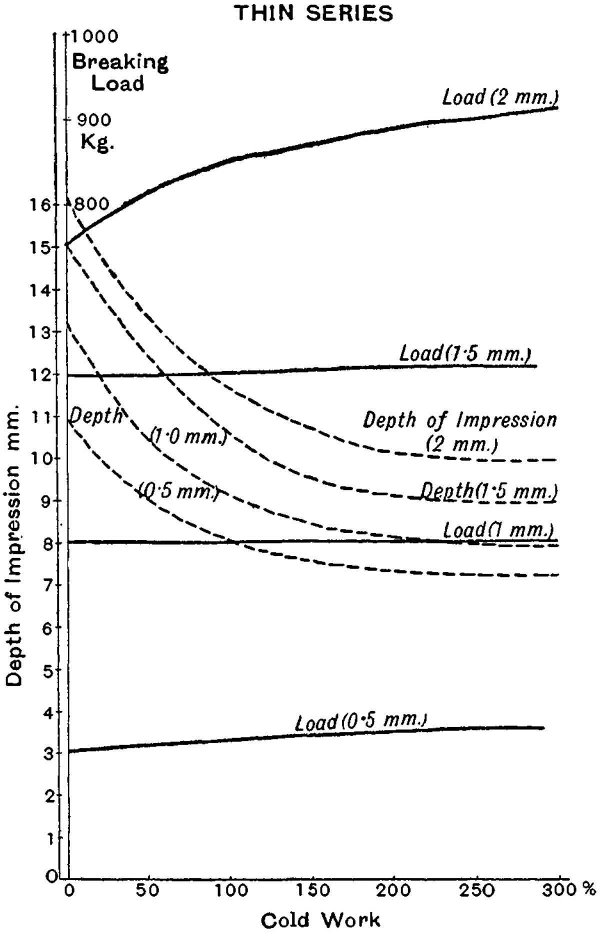


FIG. 19.—Cupping Tests : Variation in Breaking Load and Depth of Impression with Cold Work. Test pieces of thickness specified (2·0, 1·5, 1·0, and 0·5 mm.).

It shows clearly that the very slight increase in the Breaking Load due to the cold work is only obtained at the expense of the Depth of Impression at rupture.

We may therefore deduce the following general conclusion :

The absolute minimum cold work should be specified for sheet aluminium required for pressing or other work of a similar nature. The amount of cupping, which annealed sheet will stand, is clearly superior to that which sheet, worked even very little, can support.

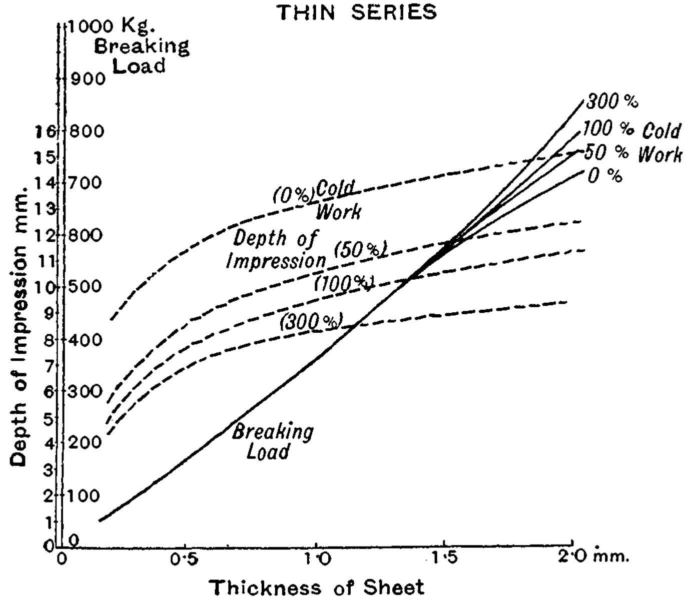


FIG. 20.—Cupping Tests: Variation in Breaking Load and Depth of Impression with thickness, at specified amounts of Cold Work (0, 50, 100 and 300 %).

Fig. 20, which is derived from Fig. 19, shows the variation of Breaking Load and Depth of Impression with thickness in the case of test pieces having been subjected to 0 %, 50 %, 100 %, and 300 % cold work respectively.

It shows that an increase of thickness must be resorted to, if an increased cupping value is desired.

CONCLUSION. Whatever the thickness, all sheet destined for pressing should be annealed, and this condition should be included in specifications.

II. *Variation of Depth of Impression and Breaking Load with increasing annealing temperature, after varying amounts of Cold Work.*

Investigations were made on test pieces of the thin series: Type I*a* (0·5 mm.) and Type I*d* (2·0 mm.), taken from sheet cold

worked to 50 %, 100 %, and 300 %. Figs. 21, 22, and 23 summarise the results obtained on Type I*a* (0·5 mm. thick). They show that the maximum values of the Depth of Impression and Breaking Load are reached in the region 375°–425°, and these values remain approximately constant up to 600°.

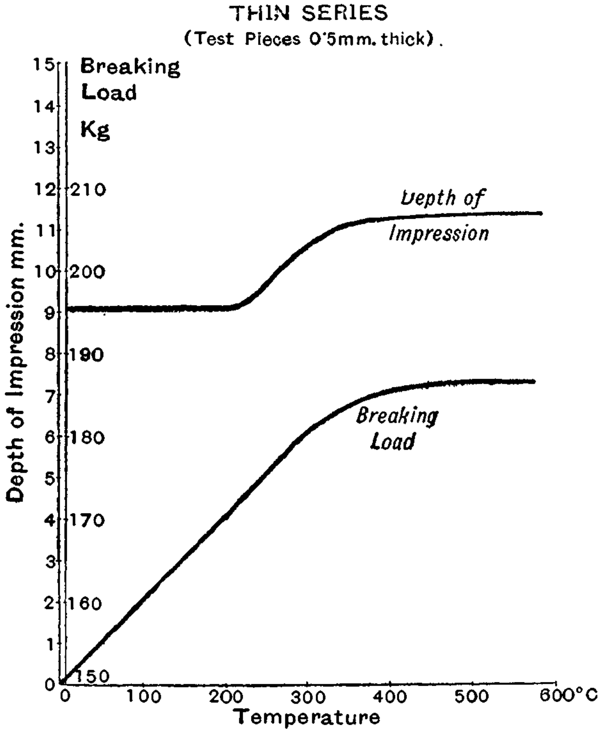


FIG. 21.—Cupping Tests: Variation in Breaking Load and Depth of Impression on Annealing after 50 % Cold Work.

They show, further, that the final results (Depth of Impression and Breaking Load) are higher as the initial cold work is greater.

The following table summarises the results:—

SHEETS 0·5 mm. THICK

	After Complete Anneal	
Initial Cold Work	*Breaking Load*	*Depth of Impression*
50 %	185 kg.	11 mm.
100 %	195 kg.	12 mm.
300 %	200 kg.	12·5 mm.

Figs. 24, 25, and 26 give the results for Type I*d* (2·0 mm. thick). They show that for sheet 2·0 mm. thick, as in the case of sheet 0·5 mm. thick, the Depth of Impression and Breaking Load reach their maximum values in approximately the same temperature range, but slightly extended (375°–450°),

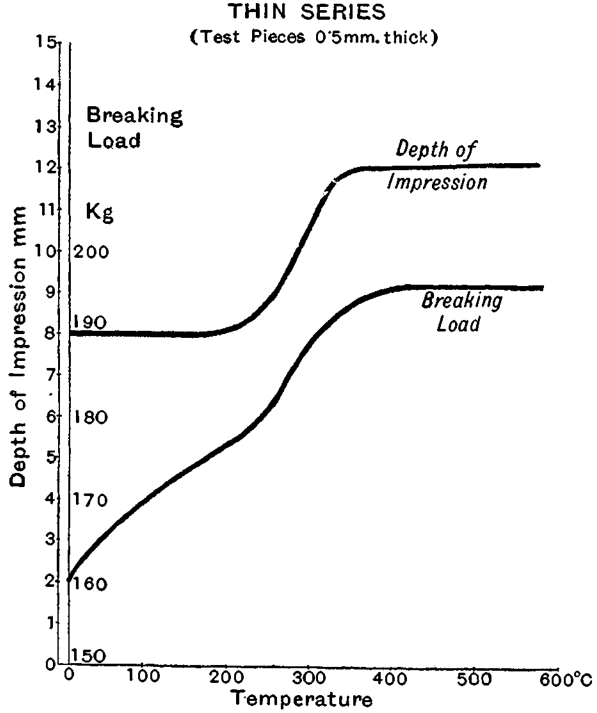


FIG. 22.—Cupping Tests: Variation in Breaking Load and Depth of Impression on Annealing after 100 % Cold Work.

and these values remain approximately constant up to 600°. The same remarks as before apply as to the relation between the initial cold work and the final values (Breaking Load and Depth of Impression at rupture). The following table may therefore be drawn up :—

SHEETS 2·0 mm. THICK

	After Complete Anneal	
Initial Cold Work	*Breaking Load*	*Depth of Impression*
50 %	850 kg.	16 mm.
100 %	880 kg.	16·2 mm.
300 %	950 kg.	16·4 mm.

D. Final Summary

In this chapter the following properties have been considered :—

(*a*) Tensile properties.
(*b*) Hardness and Shock Resistance.
(*c*) Cupping properties.

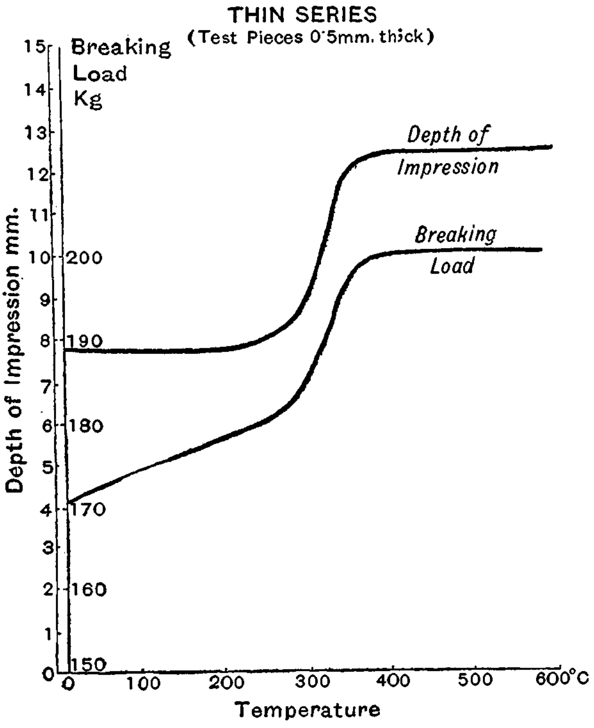


Fig. 23.—Cupping Tests : Variation in Breaking Load and Depth of Impression on Annealing after 300 % Cold Work.

The work has been carried out from a twofold standpoint—

(i) Influence of cold work.
(ii) Influence of annealing after cold work,

and without entering into minute details, already given under their respective headings, we may draw the following conclusions :—

(i) Cold Work.

This may be considered under two headings :—

(*a*) The intermediate cold-worked state during manufacture, whose effect is removed by a final anneal.

(*b*) The final cold-worked state of the manufactured product.

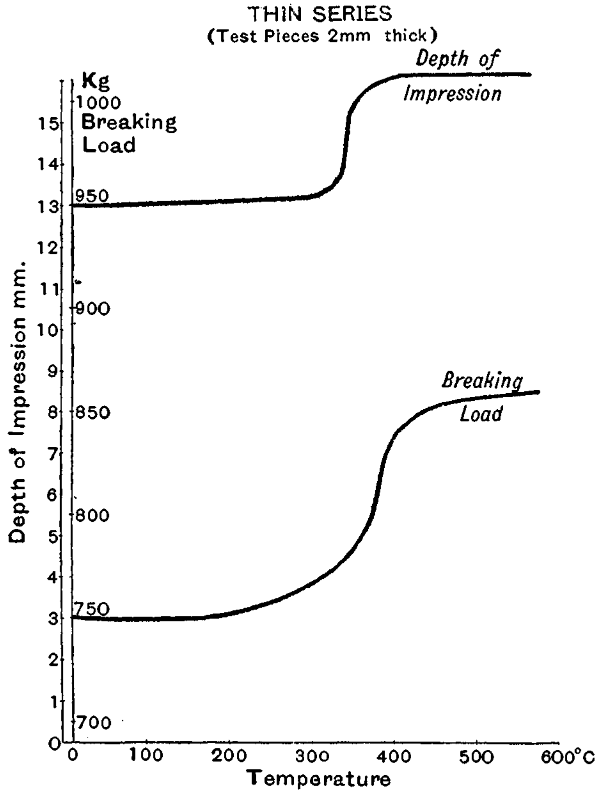


Fig. 24.—Cupping Tests: Variation in Breaking Load and Depth of Impression on Annealing after 50 % Cold Work.

(a) *Intermediate Cold Work.*

The utilisation of large amounts of cold work, 200 and 300 %, possesses certain decided advantages. It increases generally the value of the mechanical properties obtained after a complete anneal, and possesses an indubitable economic advantage in dispensing with useless intermediate anneals.

(b) *Final Cold Work.*

Cold work is far from advisable, particularly in aeronautical work. It hardly seems to constitute a stable state, and should especially be avoided in material subjected to constant vibration.

We are therefore of the opinion that aluminium should be used in the annealed condition, certainly as regards aeronautical work; the increased strength, which results from cold work, as described in this chapter, should be attained by other means, such as increase of thickness, or the employment of alloys.

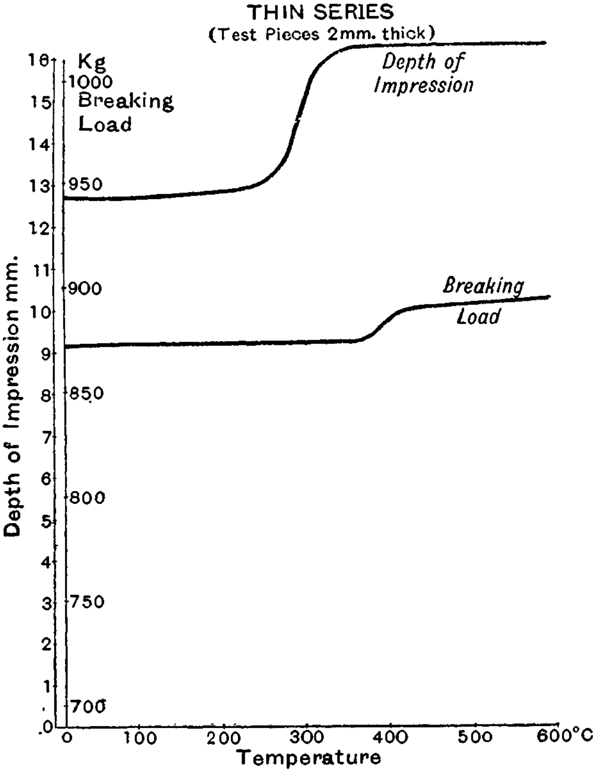


FIG. 25.—Cupping Tests: Variation in Depth of Impression and Breaking Load on Annealing after 100 % Cold Work.

(ii) ANNEALING.

We have pointed out the existence of regions of cold work, softening, complete anneal, and of falling off of ductility.

Only one region, that of complete anneal, produces a techni-

cally finished product.* This fixes an optimum mean annealing temperature of 400°, and gives, in the metal, after a suitable initial cold work (200 %–300 %), the following properties :—

Elongation % =40
Tensile Strength =11 kg. per sq. mm. (6·98 tons per sq. in.).
Elastic Limit =5 ,, ,, (3·17 ,, ,,).
Shock Resistance=8·5 kg. m. per sq. cm.
Brinell Number =23

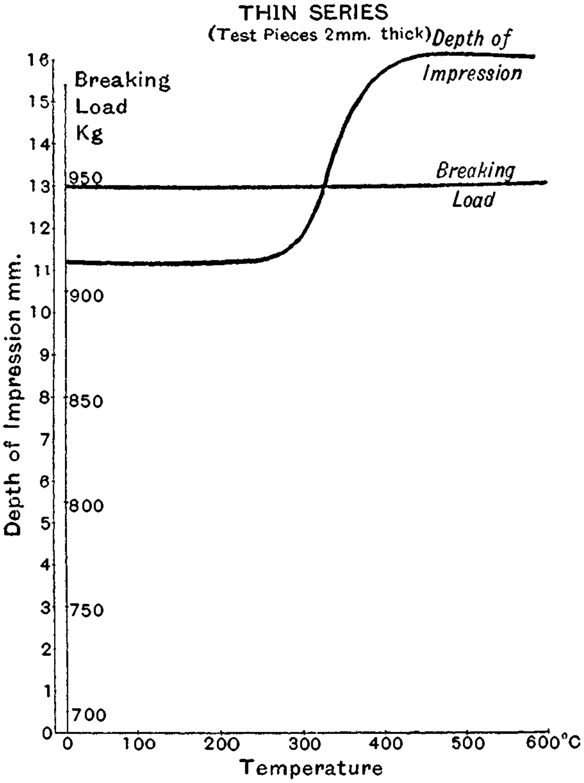


FIG. 26.—Cupping Tests : Variation in Depth of Impression and Breaking Load on Annealing after 300 % Cold Work.

* An intermediate state, producing in aluminium a Tensile Strength higher than that possessed by the annealed metal, may be studied. As we have seen, this cannot be achieved by a slight cold working, which deprives the metal of a portion of its Elongation, but only by submitting it to an anneal in the softening region—an incomplete anneal. But the improvement in the Tensile Strength, amounting to some tons per sq. in., is only realised at the expense of the Elongation, and of the regularity of the results. The great slope of the curves for Tensile Strength, and Elongation %, in this softening zone shows that a very slight variation of temperature has an enormous influence on the properties—hence the irregularity.

E. Contemporary Literature dealing with the Subject of the Mechanical Properties after Cold Work and Annealing.

As regards the variation in mechanical properties with cold work and annealing, aluminium has been subjected to very detailed investigation by Robert Anderson,* who has published the following articles :—

(1) Erichsen Tests on Sheet Aluminium ("Iron Age," 11th April, 1918, pp. 950 and 951).

(2) Annealing and Recrystallisation of Cold-Rolled Aluminium Sheet ("Metallurgical and Chemical Engineering," Vol. XVIII, No. 10, pp. 525–7, 15th May, 1918).

(3) Tests on Sheet Aluminium. Softening of Cold-Rolled Sheet by heating for an extremely short time at different temperatures. Better Properties for Drawing. Effect of Over-annealing ("Iron Age," 18th July, 1918).

For the complete report we must refer the reader to the original papers dealing with these most interesting investigations, of which we can only give an abridged summary. We may say, at once, that, where comparison is possible, there is no contradiction between Anderson's results and our own, as given in this chapter. Certain experimental methods are different.

Anderson's definition of Maximum Softening or Anneal.

The maximum softening is defined in terms of the Shore scleroscope number. The metal may be regarded as completely annealed when the scleroscope hardness is 4–5, this being the maximum softness from the point of view of practical rolling. "Sheets having this degree of hardness," says Anderson, "are as soft as is usual, though occasionally cases arise where the scleroscope number falls to 3·5."

Anderson's definition of Cold Work.

Anderson defines "cold work" or "percentage reduction of area" by the formula :—

$$\text{Reduction of area } (\%) = \frac{\text{S(initial)} - \text{s(final)}}{\text{S(initial)}} \times 100.$$

This gives, for the same deformation, a lower percentage than that calculated from our formula.

* Prior to the work of Anderson, a paper was published by Carpenter and Taverner, "The effect of heat at various temperatures on the rate of softening of cold-rolled aluminium sheet." "Journal of the Institute of Metals," 1917, and "Engineering," Vol. CIV, 1917, No. 8, p. 312.

In his paper on "Annealing and Recrystallisation of Cold-Rolled Aluminium Sheet," the author proposes particularly to show the influence of the duration of an anneal at different temperatures on the production of metal suitable for drawing and pressing under the best conditions.

The percentage reduction of area is determined. The Shore scleroscope number shows the hardness and hence the degree of softness. The Erichsen machine* shows the suitability of the metal for further work, not only by the depth of the dome, but by the large or small appearance of the grains. The anneals were carried out in a laboratory electric furnace, temperatures being measured to the nearest 5° C., and the times being recorded.

PAPER OF 15TH MAY, 1918 ("METALLURGICAL AND CHEMICAL ENGINEERING"). INFLUENCE OF TEMPERATURE AND DURATION OF ANNEAL.

Annealing cold-rolled aluminium sheet of different thicknesses for twenty-four hours at 370° gave, for a Shore scleroscope number between 4 and 5, Erichsen domes showing gross crystallisation, and metal little suitable for drawing.

Systematic tests were carried out on sheet of thickness and percentage reduction of area given in the following table:—

No.	Thickness mm.	Thickness inches	% Reduction of Area	Gauge†
1	2·58	·1087	54·85	10
2	2·05	·0841	63·30	12
3	1·70	·0650	71·60	14
4	1·32	·0512	77·60	16
5	1·09	·0401	82·60	18
6	0·79	·0321	86	20
7	0·68	·0275	88	22
8	0·54	·0220	90·50	24
9	0·40	·0169	92·70	26
10	0·30	·0128	94·50	28

MINIMUM TEMPERATURE NECESSARY FOR OBTAINING A SCLEROSCOPE NUMBER OF 4–5.

At a temperature of 300°. In the case of sheets 1 to 5 (inclusive), 60 minutes will hardly suffice to give a scleroscope number of 4–5. 30 minutes suffice for sheets 6 and 7, and 20 minutes for 8, 9, and 10.

* It should be noted that in the Erichsen machine, only the Depth of Impression, and not the corresponding Breaking Load, is measured.

† Brown and Sharpe gauges.

At 350°. 30 minutes are sufficient for sheet 1.
20 minutes are sufficient for sheets 2 and 3.
15 minutes are sufficient for sheets 4 to 10 (inclusive).

At 400°. 10 minutes are sufficient for all sheets.

At 600°. 10 minutes are sufficient for reaching a scleroscope number very near the lower limit.

Anderson's experiments, in agreement with ours, show that annealing has a more rapid effect, the greater the initial cold work. They further show that, from the point of view of working and of fineness of grain, it is necessary to investigate the greatest depth of impression given after an anneal of the shortest possible duration, and at the lowest possible temperature, consistent with a scleroscope hardness of 4–5 and a smooth Erichsen dome. Anderson has thus established the following curve (Fig. 27) which, for the conditions just stated,

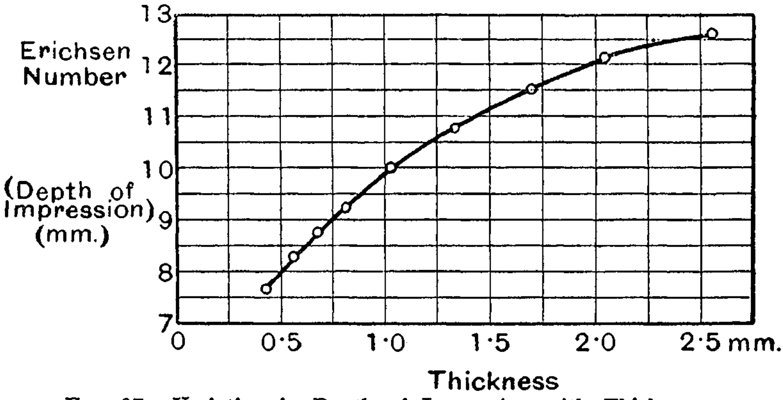


FIG. 27.—Variation in Depth of Impression with Thickness. Annealed Aluminium Sheet.

gives the curve of indentation plotted against thickness for annealed aluminium sheet. Fig. 28 gives the curve of indentation plotted against thickness for cold-rolled aluminium sheet.

RECRYSTALLISATION.

Anderson has carried out microscopic examinations of differently worked samples annealed for 30 minutes at 350°.

The samples having percentage reduction of area of 54·85, 63·30, and 71·60 respectively were not recrystallised. Recrystallisation occurred for higher percentages of deformation, which shows, again, the effect of cold work on the result of an anneal.

Anderson's work shows that prolonged annealing is very harmful, and also that not only must the temperature be carefully selected, but also the minimum time required at this temperature. We have determined this minimum time by tests preliminary to the annealing experiments. The times thus determined are different from those of Anderson, for they

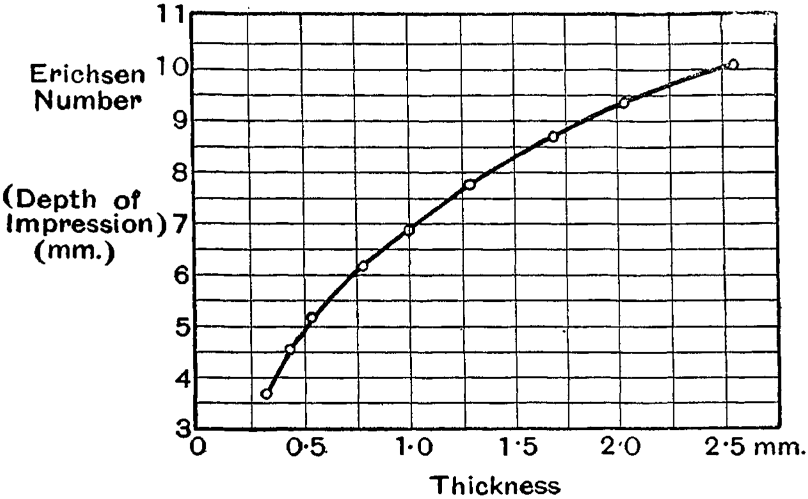


FIG. 28.—Variation in Depth of Impression with Thickness. Cold-Rolled Aluminium Sheet.

refer to annealings in liquid baths (oil or salt), for which the length of time is different from that required in electric or gas furnaces.

PAPER OF 18TH JULY, 1918 (" IRON AGE ").

Returning to the question in this paper, Anderson discusses the harmful effects of prolonged annealing—" over-annealing."

He points out, first of all, the inferior results, as regards the grain size of the metal, of annealing aluminium sheet, 1·70 mm. thick (·0650 in., No. 14 gauge) for 25 hours at 370°, and shows the good results obtained by annealing metal of this thickness for 2 hours at 400°. The best results are obtained by very short anneals (cf. Fig. 29, showing the effect of annealing for different lengths of time at 430°)—considerations which, from the industrial and commercial standpoint, are of value.

Further, two types of anneal may be distinguished :—

(i) Intermediate.
(ii) Final.

Intermediate anneals can be carried out in the neighbourhood of the upper limit of the region of complete anneal, 450° or even 500°, employing the shortest possible time consistent with the softening of the metal. The employment of a temperature higher than those indicated, necessitates an extremely short

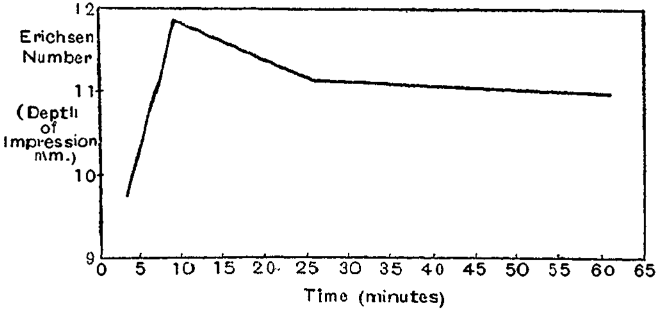


FIG. 29.

anneal; a slight variation, therefore, in the length of time, difficult to avoid in works practice, may lead to large irregularities.

Final anneals, which must be carried out very precisely, in order to obtain regularity in the finished product, are conducted at the temperature specified above (i.e. 375°–425°) for the minimum length of time possible, which is easily determined for the particular temperature employed.

CHAPTER IV

MICROGRAPHY OF ALUMINIUM

THE micrography of pure aluminium presents special difficulties, not generally met with in the case of its alloys. The numerous set-backs experienced in this method of examination have hindered its standardisation.

The difficulties lie as much in the technique of polishing as in that of etching.

POLISHING.

The difficulty in polishing is due chiefly to the softness of the metal, which tends to flow or to become hardened under the pressure employed; this pressure must, therefore, be very slight—a matter of practice and touch.

The particles and dust of the emery paper become embedded in the pores of the metal. R. J. Anderson pointed out this difficulty and recommended the following method of overcoming it, based upon that of Gwyer :—

"The surface is levelled off with a fine file, followed by dry, coarse emery paper, and then by No. 0. The operation is continued, using papers No. 00, 000 and 0000, covered by a thin layer of paraffin wax. This paraffin film prevents the entrance of the fine emery particles into the metal, and gives a very satisfactory polish. Melted paraffin is poured on the surface, and smothered with a flat, warmed file. The papers are secured to wooden boards or to a polishing disc. The last scratches, caused by the 0000 paper, are removed by polishing on cloth with fine Tripoli and water. The darkening of the surface caused by the Tripoli is removed by polishing on a fine cloth with a non-alkaline metal polish."

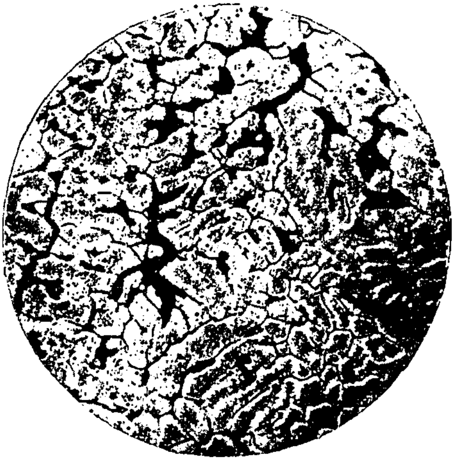
ETCHING.

Both potash and soda (KOH, NaOH) have been used as etching reagent, the black deposit which forms being removed by immersion in a dilute solution of chromic acid, as recommended by Archbutt.

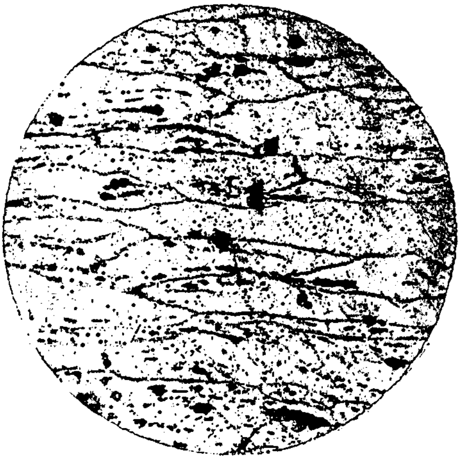
The best results have been obtained using hydrofluoric

PLATE I.

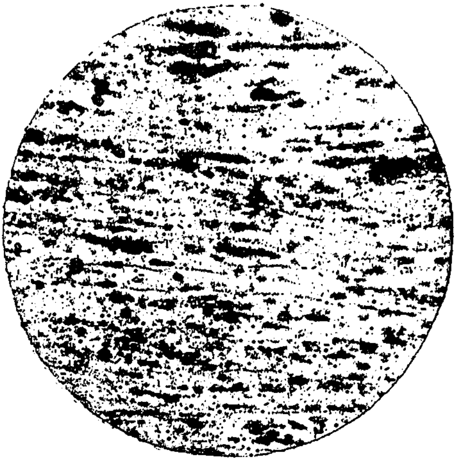
PHOTOGRAPH 1.
ALUMINIUM INGOT. CHILL CAST.
×40.
(Robert J. Anderson.)



PHOTOGRAPH 2.
ALUMINIUM INGOT. SAND CAST.
×50.
(Robert J. Anderson.)



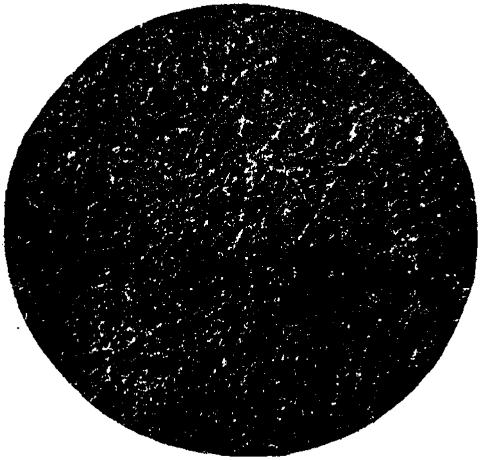
PHOTOGRAPH 3.
ALUMINIUM. COLD WORKED (50 %).
×100.



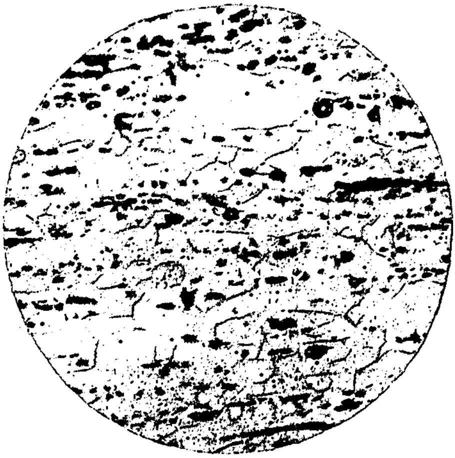
PHOTOGRAPH 4.
ALUMINIUM. COLD WORKED (100 %).
×100.

To face page 57

PLATE II.



PHOTOGRAPH 5.
ALUMINIUM. COLD WORKED (300 %).
×60.



PHOTOGRAPH 6.
ALUMINIUM. COLD WORKED (300 %) AND SUBSEQUENTLY ANNEALED AT 350° FOR 10 MINUTES.
×100.

PHOTOGRAPH 7.
ALUMINIUM. ANNEALED AT 595° FOR 60 MINUTES.
×50.
(Robert J. Anderson.)

PHOTOGRAPH 8.
ALUMINIUM. ANNEALED AT 595° FOR 4 HOURS.
×50.
(Robert J. Anderson.)

To face page 57

acid (HF), as suggested by Brislee, employing a mixture of one part of fuming hydrofluoric acid and eight parts of water. The section is plunged into this liquid, and the blackening of the surface is removed by immersing for some seconds in concentrated nitric acid. Hydrogen fluoride vapour may equally well be employed for etching. To give good results, the hydrofluoric acid should be chemically pure, and should be preserved and used in vessels coated with paraffin.

RESULTS.

Micrographs of aluminium are given in Plates I and II. Photographs 1 and 2, taken from the work of R. J. Anderson, refer to chill and sand castings.

The first shows the dendritic structure, well known in cast metals. The second shows crystals of aluminium surrounded by segregations.

Photographs 3, 4, and 5 refer to aluminium cold worked to 50, 100, and 300 % respectively. The flow lines in the direction of rolling are evident.

Photographs 6, 7, and 8 show the effect of annealing after cold work. Photograph 6 shows the result of annealing, at 350° for 10 minutes, aluminium previously cold worked to 300 %. The lines of flow due to cold work have not disappeared, but underneath these striations, still visible, a fine cellular network, characteristic of annealed metal, can be seen. The striations due to cold work only disappear on heating either for a longer period or to a higher temperature. Photographs 7 and 8 show the characteristics of a metal whose Elongation has diminished as a result of over-annealing.

The thermal and mechanical treatment of aluminium can thus be controlled, up to a certain limit, by micrographic examination, as can also the purity of the metal and the absence of dross.

CHAPTER V

PRESERVATION OF ALUMINIUM

We have thought it best to consider, in a special chapter, the subject of the preservation of aluminium, or, if it be preferred, of its changes under the influence of physical, chemical, or mechanical agencies.

The explanation of this change refers, partly, to indisputable phenomena, and partly to hypotheses which probably have the advantage of lying very near the truth. It is a fact that aluminium changes under certain conditions.

Ditte, H. Le Chatelier, Ducru, Heyn and Bauer have made investigations and published papers on this subject.

Effect of Atmospheric Agencies

The effect of atmospheric agencies can be summarised as follows:—

Air.

Sheets of aluminium were protected from the rain, and exposed to the atmosphere by Heyn and Bauer, and after two hundred days had not changed in appearance.

Ditte explains this apparent unchangeability by the fact that a very thin film of alumina is formed, which protects the rest of the metal from all change.

Water.

Aluminium is attacked by distilled water, hydrated alumina being deposited. According to Ditte, this thin layer of alumina protects the aluminium from further oxidation.

Air and Water.

Air and ordinary water, acting alternately, have less effect than water alone.

Air and Salt Water.

The views of Ditte upon this subject are as follows:—

"Whenever aluminium is in contact with the atmosphere, salt water, sea water, or brackish water, the metal becomes

coated with a more or less compact layer of alumina, possibly mixed with other soluble salts.

After the aluminium has been removed from the liquid, the change will continue to take place, if the metal has not been entirely freed from this coating and has not been sufficiently washed so as to remove from it all traces of alkali.

Wherever the external surface of the metal has allowed a trace of the sea salt to penetrate, the action will slowly continue, proceeding the more rapidly as the oxidised substance is more hygroscopic, and permits the possible chemical reactions to take place more easily."

In these results, the molecular state of the metal (anneal, degree of cold work, etc.) has not been taken into account. Then the following questions arise :—

Are these changes solely due to chemical actions, oxidations, tending to change the composition of the metal ?

Are they due to disintegrations, depending upon the molecular state of the aluminium ?

Are they due to the ill-effects of cold work, giving rise to a sort of spontaneous anneal, accompanied by disintegrations and cracks ?

We have particularly studied this phenomenon in the brasses, whose preservation was irretrievably endangered, if, after cold working, a certain minimum anneal (350°) had not been previously carried out.

Cartridge cases and artillery shells suffered very largely from this fault before the remedy, just described, was applied.

In other words, is the disintegration of aluminium connected with chemical causes or mechanical causes or does it not depend on these two causes together ?

The following literature, referring to different cases of alteration, will enable us to see, up to a certain point, what are the respective parts played by these two types of phenomena.

Ducru* observed the alterations of aluminium for the first time about 1894 in the case of wires of this metal, used as telegraph wires in the Congo or Dahomey from the coast to the interior. In a month, the wire, which had a Tensile Strength of 23 kg. per sq. mm. (14·6 tons per sq. in.), had become grey, and changed to an extremely weak substance. Chemical analysis showed no oxidation. Hence there was no change of a chemical nature.

* *See* 2nd Report, 1911, of the meeting of the French and Belgian members of the International Association for testing materials, March 25th, 1911. Burdin, Angers.

The same phenomena were observed in the case of a sheet of aluminium at Havre, exposed alternately to air and sea water; in this instance, at the end of three months, there was superficial oxidation.

This changed layer was removed by planing so as to leave only the sound portion. Tests on this showed that the Tensile Strength had fallen from 22 to 4 kg. per sq. mm. (14 to 2·54 tons per sq. in.). At all events, there was an initial cold work clearly indicated.

In 1897, Ducru observed the alteration of aluminium in utensils made by pressing. This alteration took place on the bottom of the utensil in the following manner:—

There was a diminution in the metallic lustre of the aluminium, and the appearance of a grey colour, becoming more pronounced. The altered portion possessed no strength, while analysis showed only 4 to 5 % of the metal to be changed to alumina.

Similar observations were made about 1911, on utensils, 1 mm. in thickness, made by pressing, and intended for domestic and culinary purposes. The same changes were apparent, and the bottom of the vessel could be pierced by simple pressure of the finger. Analysis showed that 2·7 %, 3·7 %, and 3·5 %, according to the sample, was changed to alumina, and Ducru drew the following conclusions:—

"In conclusion, the alteration of aluminium appears, at least in certain cases, to have one peculiar characteristic, namely, that it is not an oxidation effect, for that seems to affect only a small portion of the metal, and it is, on the other hand, accompanied by a diminution in mechanical strength, which causes serious trouble."

Then, if the phenomena be investigated more closely, it is evident that the unfortunate incidents mentioned have occurred in the case of excessively cold-worked aluminium—wires, sheets, or pressed utensils.

The external agencies play the part of accelerators, assisting the breakdown of equilibrium, which, in their absence, would probably only have been delayed.

We have, ourselves, verified these disintegrations due to cold work. We have not carried out experiments on aluminium, but the investigations we have made on the cold working of brass lead us to infer that the working of aluminium cannot be irrelevant to these disintegrations.

From the micrographic standpoint, worked aluminium, similarly to worked brass, assumes a striated appearance,

showing crystalline deformation in the direction of the mechanical work—a condition in which instability is probable.

For aeronautical use, where security is essential, the need for an anneal is clearly proved,—a conclusion supported by the arguments already given. For strengths higher than that of annealed aluminium, resource must be had to its alloys.

For purposes in which safety is not of prime consideration, and in which the high strength obtained by the working of aluminium is desirable, the problem takes on another aspect.

The practical durability of cold-worked aluminium will be a predominant factor to be considered in solving the problem of the practical and economical uses of which it is capable (for wires and cables for electrical conductors).

CHAPTER VI

SOLDERING OF ALUMINIUM

After having discussed the physical, chemical, and mechanical properties, we may say a few words about the soldering of aluminium. This soldering is not without difficulties, which are both of a physical and chemical nature.

(*a*) Physical Difficulties.

Coefficient of Expansion. Aluminium possesses a high coefficient of expansion, which must be taken into consideration in order to avoid breakdowns. As its tenacity is low at high temperatures, there is a possibility of rupture occurring owing to the relative contraction as the joint cools down.

Melting Point. The low melting point of aluminium, 650°, is also a disadvantage. If the temperature of the blowpipe (generally high) is not very carefully regulated, the melting point of the metal may be reached or even exceeded, thus damaging the articles to be soldered, to say nothing of the deterioration of properties resulting from overheating, which cannot be remedied by subsequent cold work, followed by an anneal at a suitable temperature and for an appropriate time.

(*b*) Chemical Difficulties.

These difficulties arise from the impurities of the metal and of the soldering alloys.

Impurities. The impurities have been divided into three groups :—

Group I. Iron-Silicon Group. Iron and silicon have harmful effects in aluminium solders.

It is impossible to eliminate these impurities completely, but their amount must be restricted according to the specifications we have laid down.

The alloys of iron and silicon with aluminium are very weak and constitute the weakest parts in the article. The overheating, due to the soldering, facilitates, therefore, the formation of a very weak system, consisting of the alloys of these

impurities with the aluminium, which is liable to lead to rupture. Hence a metal must be used which does not contain larger amounts of impurities than the maxima previously specified.

Group II. Minor Impurities. If these do not exceed the maxima stipulated, they do not cause any serious inconveniences.

Group III. Alumina. The formation of alumina is unavoidable during soldering, and this gives rise to the most serious difficulties. The presence of alumina between the two sheets to be soldered hinders the soldering, if means are not taken, during the operation, to remove it. For this purpose, a flux is used, which must fulfil certain prescribed technical conditions.

The following flux is recommended by "L'Union de la Soudure Autogène":—

Lithium chloride	15 %
Potassium chloride	45 %
Sodium chloride	30 %
Potassium fluoride	7 %
Sodium bisulphate	3 %

The bisulphate of soda, under the action of heat, reacts with the chlorides and fluorides forming hydrochloric and hydrofluoric acids, which attack the alumina, producing the volatile chloride and fluoride of aluminium.

Soldering Alloys.

Generally, the alloys for soldering aluminium are not satisfactory. In order to effect soldering, i.e. for alloying to take place, the temperature must be relatively high and then the disadvantages pointed out as a result of overheating are to be feared.

Galvanic couples, in presence of salt solutions, may lead to disintegrations of the metal.

To sum up, we are forced to the following conclusions concerning the soldering of aluminium:—

(1) The metal used must be as pure as possible.
(2) A flux must be employed to remove the alumina, which hinders soldering.
(3) Preferably, autogenous welding should be used.

BOOK II

ALLOYS OF ALUMINIUM

CLASSIFICATION OF ALLOYS

As regards abridged notation and nomenclature of alloys, we shall conform to the methods prescribed by the Permanent Commission of Standardisation in Paper A2, July 28th, 1919, on "The Unification of Nomenclature of Metallurgical Products."

Thus, for example, the abridged notation of an alloy may be

$$Al \quad Cu_{11} \quad Sn_3 \quad Ni_1$$

showing that we are dealing with an alloy of aluminium containing

11 % copper.
3 % tin.
1 % nickel.

According to the classification adopted (see page xi), we have to consider

(1) Light alloys of aluminium for casting purposes.

(2) Light alloys of aluminium of great strength (Tensile Strength greater than 35 kg. per sq. mm. (22·22 tons per sq. in.)).

A typical light alloy of these two classes has a density less than 3·5, and in the majority of light alloys, as we shall see, the density is less than 3.

(3) Heavy alloys of which aluminium is a constituent, comprising especially the "cupro-aluminiums," that is to say, alloys of copper and aluminium containing 1–20 % of aluminium with less than 1 % of other impurities.

Copper being the principal constituent, an alloy of copper containing 10 % of aluminium, for example, would be represented by the symbol $CuAl_{10}$ and the special cupro-aluminium alloy containing 9 % of aluminium and 1 % of manganese by $CuAl_9Mn_1$.

These alloys are often known as aluminium bronzes, though the name aluminium bronze should be restricted to alloys of copper and tin containing aluminium, such as the aluminium bronze for bearings whose symbolic notation is $CuSn_{44}Al_3$.

Moreover, in the nomenclature of alloys, we shall invariably put first the principal metal, followed by the other metals which are present as added constituents. Thus the name—"aluminium-zinc alloys"—refers to those rich in aluminium and which therefore come under the heading of light alloys, while the name "zinc-aluminium alloys" refers to those rich in zinc, which are not, therefore, classed as light alloys, but as heavy alloys. These heavy alloys are only of value in aeronautical construction if some special properties compensate for their weight.

After dealing with the alloys of the three groups of which we have made a special investigation, we shall summarise shortly, in a special section, the properties of the principal alloys in the group which have been studied by previous investigators. Before discussing, in the following chapters, the investigations on these alloys, we think it advisable to recall the important part played by copper in the alloys of aluminium. Since the majority of the alloys of these three groups are affected by this constituent, it seems suitable to consider it separately, before entering into a detailed study of each.

Equilibrium Diagram of Copper-Aluminium Alloys.

The diagram was first established by H. Le Chatelier, then by Campbell and Mathews, Carpenter and Edwards, Gwyer, and Curry. There are few differences between these various diagrams.

We give Curry's diagram (Fig. 30), and the results of the micrographic examination may be summarised as follows:—

Three regions may be distinguished:—

First Region. Alloys rich in copper (100 %–86 % by weight of copper).

In the region extending from 100 %–92 % of copper, the alloy consists of a solid solution, known as α, while from 92 %–86 % of copper the solid solutions α and γ are present.

The latter region can be further divided into two, namely:—

92 %–88 % copper $\left\{\begin{array}{c}\text{solution } \alpha \\ + \\ \text{eutectic } (\alpha+\gamma)\end{array}\right.$

88 %–86 % copper $\left\{\begin{array}{c}\text{solution } \gamma \\ + \\ \text{eutectic } (\alpha+\gamma)\end{array}\right.$

At 88 % of copper, therefore, the alloy consists of the eutectic $(\alpha+\gamma)$, formerly called β. This use of the name β is incorrect, since the constituent β corresponds with austenite in steels—we shall not employ it. The solution α would correspond, in steels, with α iron, the solution γ with cementite, and the eutectic $(\alpha+\gamma)$ with pearlite.

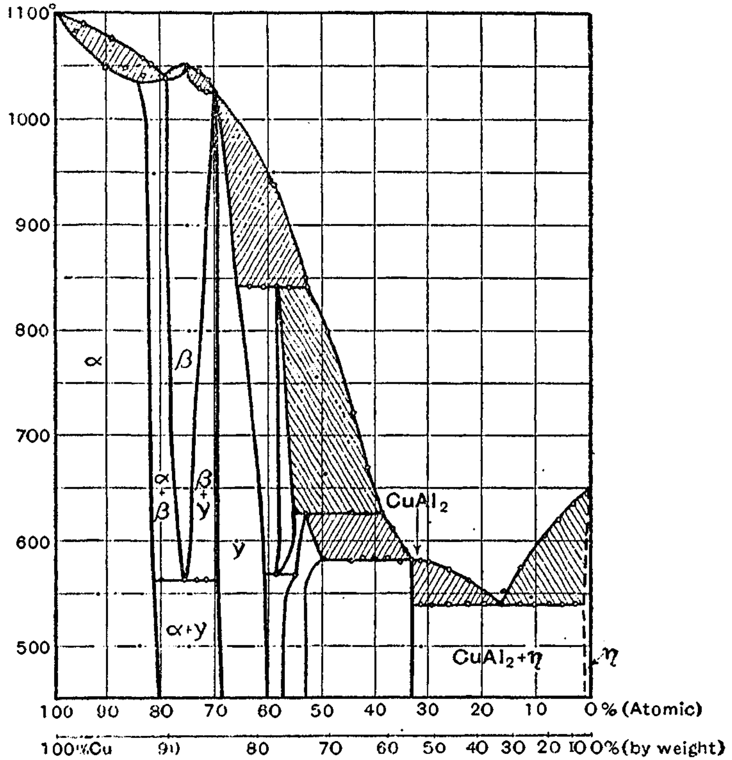


FIG. 30.—Copper-Aluminium Diagram (after Curry).

The heavy alloys of great strength, that is, the cupro-aluminiums, or aluminium bronzes, are contained, approximately, in the region from 92 % to 88 % of copper, i.e. the region corresponding with the solution α and the $(\alpha+\gamma)$ eutectic.

Second Region. This is a middle zone, extending from 86 % to 54 % of copper, in which a certain number of constituents exist which have been differently named by the various investigators. The corresponding alloys are weak and of no industrial importance.

Third Region. This extends from 54 % to 0 % of copper. The alloys consist of the constituents $CuAl_2$ and η, the latter being a solid solution of copper in aluminium containing a very low percentage of copper.

This region may be divided into two :—

(*a*) Between 54 % and 30 % of copper, in which the constituents $CuAl_2$ and eutectic occur, the eutectic being $(CuAl_2+\eta)$.

(*b*) Between 30 % and 0 % of copper, in which the constituent η and the eutectic just mentioned occur.

It must be noted that, for low amounts of copper, the constituent η is present alone, without any eutectic. At 30 % of copper the alloy would consist only of the $(CuAl_2+\eta)$ eutectic.

The only part of this region which is of industrial importance is that extending from 12 % to 0 % of copper, which corresponds with the light alloys of low strength for casting purposes.

Hence we shall only deal with the two extremities of the equilibrium diagram of the copper-aluminium alloys.

PART III

LIGHT ALLOYS OF ALUMINIUM FOR CASTING PURPOSES

We have no intention of considering the details of the casting of aluminium, and have no wish to discuss all the possible alloys of aluminium used, or usable for this purpose. We shall simply give the results of experiments carried out on a certain number of these, particularly those which have been used in aeronautical work. We shall conclude this account with a summary of the properties of certain other alloys, as investigated and tested in France and other countries.

First of all we shall summarise the different legitimate requirements as regards the quality of aluminium and its alloys used for casting.

Properties of Aluminium Casting Alloys.

The following are the most important, especially from the aeronautical standpoint.

(1) Lightness.
(2) Minimum of blowholes and porosity.
(3) A sufficiently great Tensile Strength, Elastic Limit, and Hardness.

And, for articles used at high temperatures, such as pistons, motor cylinders, etc. :—

(4) A certain minimum hardness throughout the range of temperature experienced.
(5) Maximum thermal conductivity and specific heat. We may say at once that pure aluminium will not satisfy all these requirements, and that it is even difficult to find an alloy that will completely fulfil all these conditions, which we shall discuss in turn.

(1) *Lightness.*

The pure metal best satisfies this condition, the alloys rich in magnesium alone being superior in this respect.

The addition of other constituents, however, ought not to deprive the alloy of the lightness due to the aluminium.

One of the great advantages of the low density consists in the removal of the critical period of vibration* outside the regular period of the moving system. A critical period of vibration obtains, when there is coincidence between the frequency of the particular part in question and the displacement frequency of the system of which it forms a part—a persistence of these conditions may lead to rupture.

If aluminium be substituted for steel, and the area of cross section be doubled, there is still a reduction in weight and a vibration frequency four times greater which displaces the critical resonance range a certain number of octaves, thus making harmful coincidences more improbable.

A maximum density of 3 should be specified.

(2) *Minimum of Blowholes and Porosity.*

The cast article must be sound, having as few blowholes as possible.

A high percentage of alumina seems to cause blowholes in the cast aluminium article, and hence renders it useless.

Porosity must be avoided. In the pistons of aeroplane engines, porosity invariably leads to erosion, on account of the hot gases being continually forced through the article. Porosity also prevents watertightness. It is detected by special tests and is usually avoided by the skill of the founder.

(3) *A sufficiently great Tensile Strength, Elastic Limit, and Hardness.*

Pure cast aluminium has, in the cold, the following properties :—

Tensile Strength (average)		=7 kg. per sq. mm. (4·45 tons per sq. in.).
Elastic Limit	„	=3·5 kg. per sq. mm. (2·22 tons per sq. in.).
% Elongation		=7
Shock Resistance		=2 kg. m. per sq. cm.
Brinell Hardness		=23

and is unsuitable for most articles.

It is obvious that a Tensile Strength comparable with that obtained after forging or rolling cannot be expected in a cast alloy.

* Cf. Fleury and Labruyère, "Des emplois de l'Aluminium dans la construction des Machines" (Dunod and Pinat, 1919).

From this point of view the requirements must be modest, varying between 8 and 20 kg. per sq. mm. (5·08 and 12·7 tons per sq. in.), according to the added constituents and the method of casting (chill or sand).

The Elastic Limit is generally very near the Tensile Strength, and is sometimes indistinguishable from it.

The Elongation is always very low, and the Hardness varies as does the Tensile Strength.

Very little must be expected as regards Shock Resistance also, no cast alloy having, to our knowledge, an appreciable shock resistance; they are all more or less brittle.

It is essential to take this fact into consideration in specifying the method of working for cast articles.

For articles subjected to high temperatures, which is the case in the majority of parts of machines, the following properties are required :—

(4) *A certain Minimum Hardness up to the Maximum Temperature reached.*

Pure aluminium does not possess sufficient hardness as the temperature rises. Parts of engines, such as cylinders and pistons, may reach a temperature of 200°–300°.

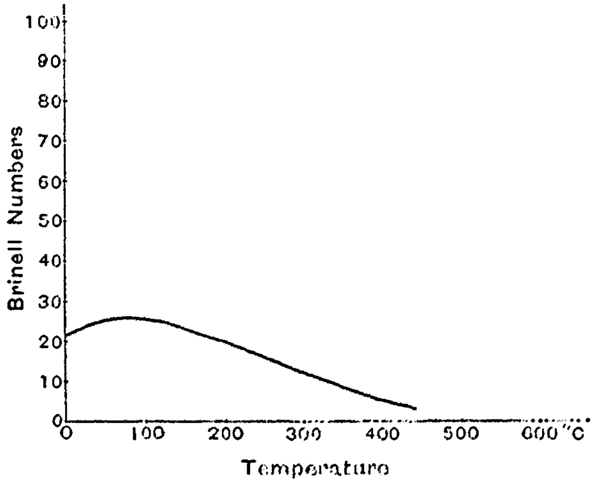


FIG. 30*b*.—Hardness of Aluminium at High Temperatures under 500 Kg. load.

In order to avoid collapse, those parts subjected to stress should possess, throughout the whole range of temperature experienced during working, certain minimum properties.

As regards hardness, this can be expressed approximately by a Brinell number of about 30 under a load of 500 kg.

This number is greater than that of aluminium in the cold, and necessitates an original hardness of 50 to 60.

Tests have been carried out on a certain number of alloys in order to examine these properties at high temperatures.

Fig. 30*b* shows the hardness of aluminium at different temperatures, and enables us to see how the hardness is increased by the addition of various constituents.

(5) *A Maximum Thermal Conductivity and Specific Heat.*

A high conductivity prevents local heating, which rapidly causes deterioration, and renders the article useless.

Alloys of aluminium possess great advantages in this respect. We know that the conductivity of aluminium is 36, that of silver being 100 and of copper 75·11—it is third as regards thermal conductivity. This fact is of very great importance ; it renders the employment of aluminium alloys for pistons very successful.

On the other hand, the specific heat of aluminium is very high, which reduces the rise in temperature. This property, added to the high thermal conductivity, causes aluminium pistons to become far less heated in use than pistons of cast iron.

The temperature reached is lower than that of decomposition of the lubricating oils, so that carbonaceous deposits, similar to those produced on cast-iron pistons, are not formed on pistons of alloys of aluminium—for this reason fouling and seizing do not occur.

After this short discussion we will consider individually the alloys which we have investigated or met with in practice.

ALLOYS OF ALUMINIUM FOR CASTING PURPOSES.

The following alloys have been considered :—

(*a*) Binary aluminium-copper alloys—the study of the part of the equilibrium diagram of the aluminium-copper alloys extending from 100 % to 88 % of aluminium.

(*b*) Ternary alloys—aluminium-copper-zinc.

(*c*) Quaternary alloys—aluminium-copper-tin-nickel.

We conclude the account of the tests carried out on these alloys by referring, in a special section, to certain other alloys belonging to the group, namely :—

Alloys of aluminium and tin.
Alloys of aluminium and zinc.
Alloys of aluminium and magnesium.

As far as possible, we shall compare the properties of the cast alloys with those of the same alloys when forged or rolled.

These alloys have been worked in the following manner :—

(1) *Casts.*

Some heats were cast directly into chills without runners. Ten casts were made for each alloy in cylinders 50 mm. in diameter and 50 mm. in length.

In five casts two tensile and two shock test pieces were made per cast, the operation being carried out in such a way as to obtain a tensile test piece at one end and a shock test piece at the other end of the heat, and one tensile and one shock test piece towards the middle of the heat.

In the other casts, cylindrical bars were made for hardness tests at high temperatures. These were carried out, using a 10 mm. ball and loads of 500 and 1000 kg.

(2) *Test Pieces.*

These were cast, on the one hand in chills, and on the other hand by bottom pouring, the test pieces being fed by lateral runners.

These two types of tests, the one on sand cast, and the other on chill cast test pieces, seemed indispensable in order to show the different results obtained by the two methods.

In general, casting is carried out by the latter method, while the real and intrinsic properties of the alloy are revealed by the former.

We should render ourselves liable to error, if we took, as the figure for Tensile Strength, that determined on the sand cast samples.

Tests on the sand cast test pieces indicate the success or failure of the alloy, but do not show the true properties possessed by the chill cast article.

(*a*) BINARY ALLOYS—ALUMINIUM-COPPER.

The following types are considered :—

Type I	. . . 4 %	copper.
„ II	. . . 8 %	„
„ III	. . . 12 %	„

TYPE I (4 % COPPER)

Analysis

Aluminium, alumina . . .	94·25
Copper	4·70
Iron	0·57
Silicon	0·48

Density : 2·75

Mechanical Properties (*as cast*).

The average mechanical properties may be summarised as follows :—

(a) *Tests on Sand Castings.*

Tensile Strength =11 kg. per sq. mm. (6·98 tons per sq. in.).
% Elongation =3
Shock Resistance=0·6 kg. m. per sq. cm.

(b) *Tests on Chill Cast Bars.*

Tensile Strength=13·7 kg. per sq. mm. (8·70 tons per sq. in.)
% Elongation =3·8

The Elastic Limit is approximately the same as the Tensile Strength.

In the forged or rolled state, this same alloy may give :—

Tensile Strength=20 kg. per sq. mm. (12·7 tons per sq. in.)
Elastic Limit =8 kg. per sq. mm. (5·08 tons per sq. in.)
% Elongation =10

Hardness at High Temperatures.

The results of the hardness tests at high temperatures are shown in Fig. 31.

TYPE II (8 % COPPER)

Analysis

Aluminium, alumina . . .	90·07
Copper	8·65
Iron	0·84
Silicon	0·44

Density : 2·92

Mechanical Properties (*as cast*).

The average mechanical properties may be summarised as follows :—

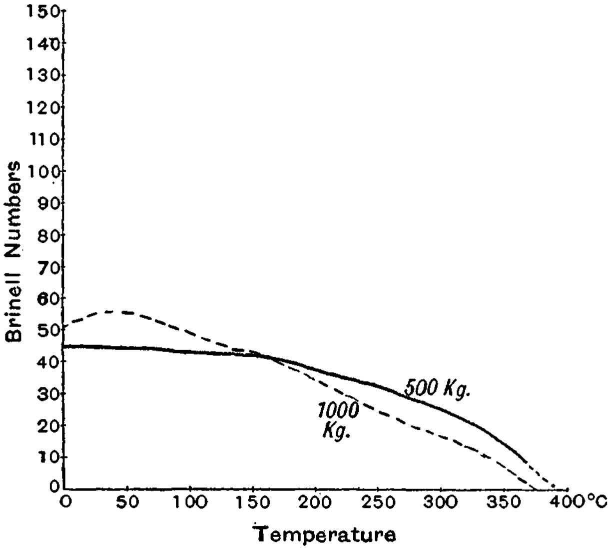


FIG. 31.—Hardness of Copper-Aluminium Alloy, containing 4 % Copper, at High Temperatures under 500 and 1000 Kg. load.

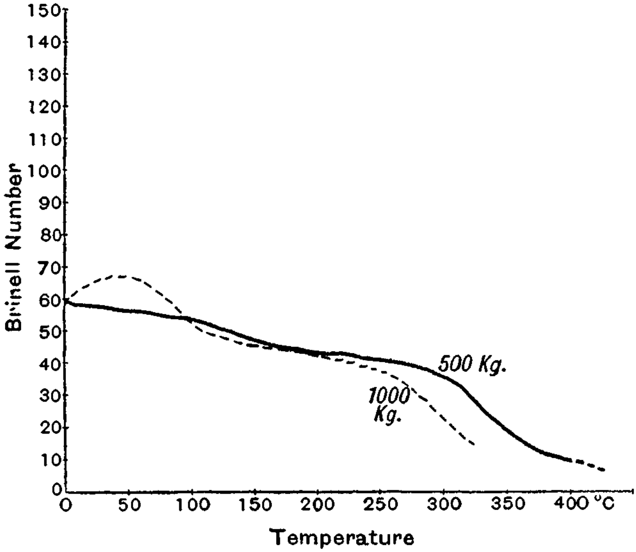


FIG. 32.—Hardness of Copper-Aluminium Alloy, containing 8 % Copper, at High Temperatures under 500 and 1000 Kg. load.

(a) *Tests on Sand Castings.*

Tensile Strength =11 kg. per sq. mm. (6·98 tons per sq. in.)
% Elongation =0·7
Shock Resistance =0·3 kg. m. per sq. cm.

(b) *Tests on Chill Cast Bars.*

Tensile Strength =12·3 kg. per sq. mm. (7·81 tons per sq. in.)
% Elongation =0·7

The Elastic Limit is approximately the same as the Tensile Strength.

The results of the hardness tests at high temperatures are summarised in Fig. 32.

Type III (12 % Copper)

Analysis

Aluminium, alumina	86·24
Copper	12·65
Iron	0·88
Silicon	0·43

Density : 2·95.

Mechanical Properties (as cast).

The average mechanical properties may be summarised as follows :—

(a) *Tests on Sand Castings.*

Tensile Strength =13 kg. per sq. mm. (8·25 tons per sq. in.)
% Elongation =0·8
Shock Resistance =0·2 kg. m. per sq. cm.

(b) *Tests on Chill Cast Bars.*

Tensile Strength =13·6 kg. per sq. mm. (8·64 tons per sq. in.)
% Elongation =1

The Elastic Limit is approximately the same as the Tensile Strength.

The results of the hardness tests at high temperatures are summarised in Fig. 33.

The variations in the hardness at high temperatures with the copper content are shown in Fig. 34.

Allowing, with a view to avoiding the possibility of collapse, a minimum Brinell hardness of 30, it is evident that the alloy

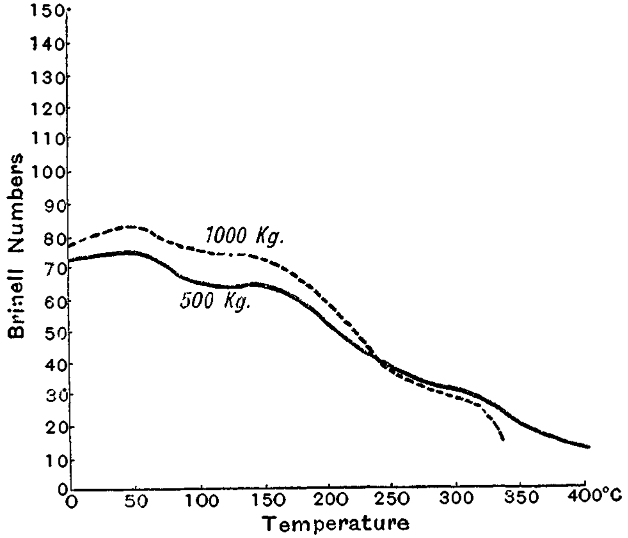


FIG. 33.—Hardness of Copper-Aluminium Alloy, containing 12 % Copper, at High Temperatures under 500 and 1000 Kg. load.

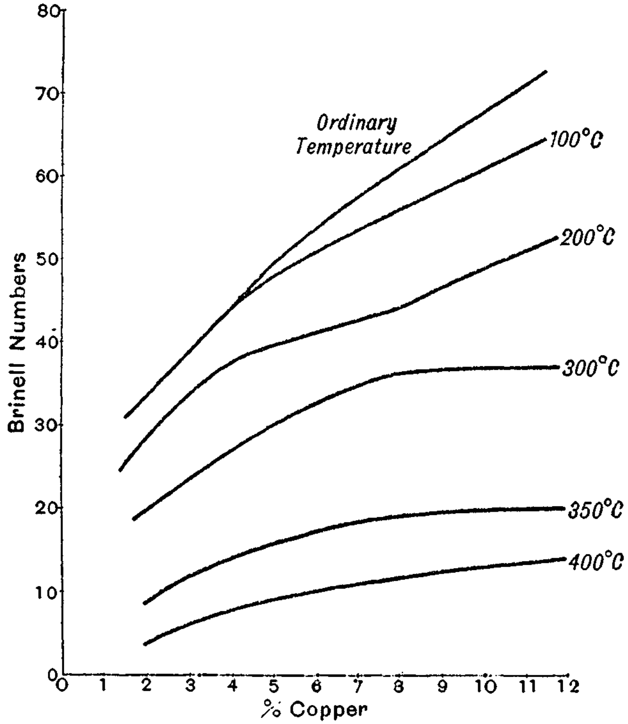


FIG. 34.—Variation in Hardness under 500 Kg. load, with Copper content at Temperatures 0°, 100°, 200°, 300°, 350°, and 400° C.

containing 4 % copper can be used for the range of temperature
0–275°,
the alloy having 8 % copper over the range 0–310°,
and the alloy having 12 % copper over the range 0–320°.

It must be noted that cold working cannot be employed to increase the hardness, since its effect must be nullified by the rise in temperature.

(*b*) TERNARY ALLOYS—ALUMINIUM·COPPER·ZINC (12–13 % ZINC, 3 % COPPER).

Analysis

Aluminium, alumina	83·75
Copper	3·10
Zinc	11·60
Lead	0·22
Iron	0·88
Silicon	0·55

Density : 2·94.

Mechanical Properties (*as cast*).

The average mechanical properties may be summarised as follows :—

(a) *Tests on Sand Castings.*

Tensile Strength = 11 kg. per sq. mm. (6·98 tons per sq. in.)
% Elongation = 0·3
Shock Resistance = 0·6 kg. m. per sq. cm.

(b) *Tests on Chill Cast Bars.*

Tensile Strength = 16·5 kg. per sq. mm. (10·48 tons per sq. in.)
% Elongation = 2·8

For the same copper content, the Elastic Limit is approximately the same as the Tensile Strength. If the amount of zinc be increased to 13 %, the values become :—

Tensile Strength = 18·4 kg. per sq. mm. (11·68 tons per sq. in.)
% Elongation = 4

The results of the hardness tests at high temperatures are summarised in Fig. 35, which shows the rapid falling off in hardness as the temperature is increased. The hardness at ordinary temperatures, however, is greater than that of the majority of other casting alloys.

(c) QUATERNARY ALLOYS—ALUMINIUM-COPPER-TIN-NICKEL.

Analysis

Aluminium, alumina . . .	84·93
Copper	10·14
Tin	3·20
Nickel	0·86
Iron	0·48
Silicon	0·27

Density : 2·98

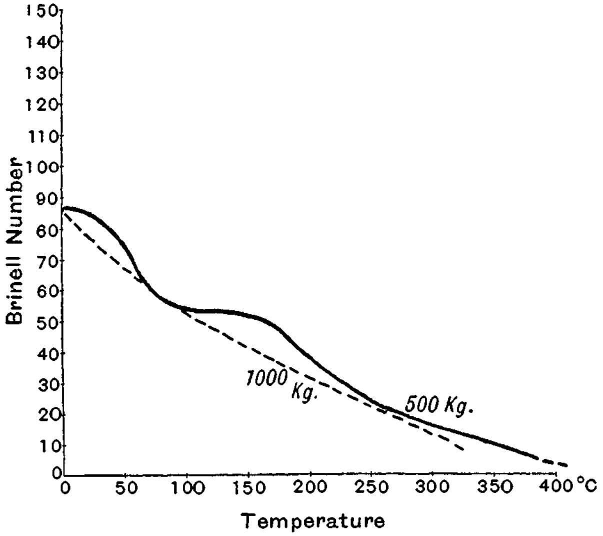


FIG. 35.—Hardness of Zinc-Copper-Aluminium Alloy, containing 12 % Zinc, 3 % Copper, at High Temperatures under 500 and 1000 Kg. load.

Mechanical Properties (as cast).

The average mechanical properties may be summarised as follows :—

(a) *Tests on Sand Castings.*

Tensile Strength =13 kg. per sq. mm.(8·25 tons per sq. in.)
% Elongation =1
Shock Resistance =0·3 kg. m. per sq. cm.

(b) *Tests on Chill Cast Bars.*

Tensile Strength =12·6 kg. per sq.mm.(8·00 tons per sq. in.)
% Elongation =0·5

The Elastic Limit is approximately the same as the Tensile Strength.

The results of the Hardness tests at high temperatures are summarised in Fig. 36.

B. PROPERTIES OF OTHER ALLOYS, GIVEN FOR REFERENCE IN A SUPPLEMENTARY SECTION

(1) ALLOYS OF ALUMINIUM AND ZINC.

(a) *Aluminium-Zinc Alloys.* The alloys of this group, which are easily utilised, are those corresponding with the shaded portion of the fusibility curve of aluminium-zinc alloys (Fig. 37). These are alloys containing 0 to 30 % zinc.

The following table due to Jean Escard* summarises the properties of chill cast bars, of bars forged at 350°, and of bars annealed at 300° for one hour after forging :—

Alloy		Treatment	Tensile Strength		Elastic Limit		Elongation %	Remarks
% Al.	% Zn.		Kg mm.²	tons in.²	Kg mm.²	tons in.²		
94·7	5·3	As cast	7·9	5·01	4·2	2·67	8·8	Used for casting and rolling
		Forged	13·6	8·64	11·3	7·18	19·0	
		Forged & annealed	9·6	6·10	2·5	1·59	30·0	
89·8	10·2	As cast	9·3	5·91	6·5	4·13	2·5	
		Forged	18·2	11·56	16·7	10·60	33·5	
		Forged & annealed	14·8	9·40	4·5	2·86	38·0	
84·0	16·0	As cast	17·1	10·86	10·4	6·60	2·0	Used especially for casting
		Forged	25·4	16·13	18·1	11·49	23·0	
		Forged & annealed	23·2	14·73	7·5	4·76	28·0	
79·0	21·0	As cast	18·4	11·68	17·1	10·86	1·0	
		Forged	31·3	19·87	22·4	14·22	14·0	
		Forged & annealed	31·5	20·00	27·6	17·53	14·5	
75·0	25·0	Forged	42·0	26·67	39·0	24·76	16·5	Rosenhain and Archbutt: Density : 3·2

All these alloys are brittle and fail under repeated impact: the brittleness is increased by rise of temperature. For example, the breaking of gear boxes of motors.

EFFECT OF TEMPERATURE (Rosenhain and Archbutt).

The Tensile Strength diminishes very rapidly with rise of temperature. The Tensile Strength of the alloy containing 25 % zinc changes from 43·3 kg. per sq. mm. (27·49 tons per sq. in.) at the ordinary temperature to 28·5 kg. per sq. mm. (18·10 tons per sq. in.) at 100°, and the rate of this diminution increases with the temperature.

We have noted in Fig. 35, referring to the ternary alloy aluminium-zinc-copper, the rapid decrease in hardness with rise

* Jean Escard, "L'Aluminium dans l'Industrie" (Dunod and Pinat, 1918).

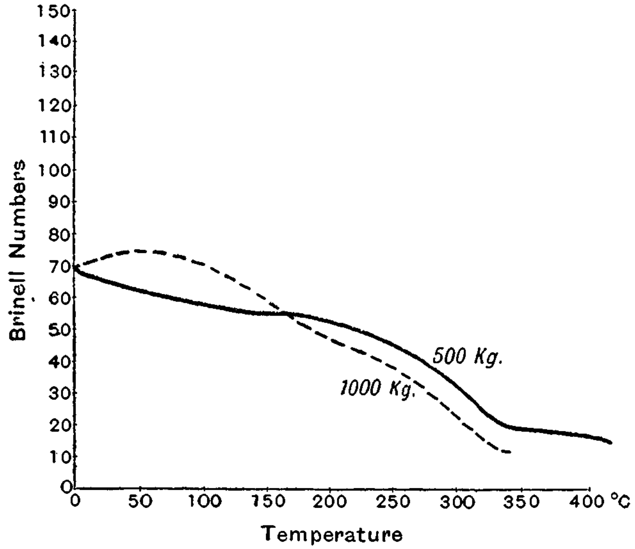


FIG. 36.—Hardness of Copper-Tin-Nickel-Aluminium Alloy, containing 11 % Copper, 3 % Tin, and 1 % Nickel, at High Temperatures under 500 and 1000 Kg. load.

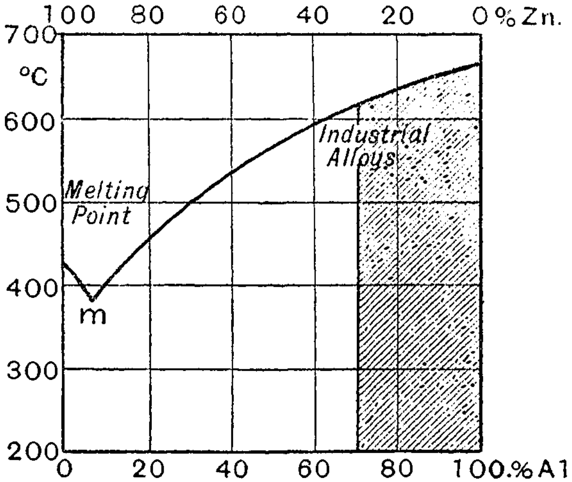


FIG. 37.—Melting-point Curve of Zinc-Aluminium Alloys.

of temperature. The Brinell number for this alloy falls from 85 under a load of 500 kg. at the normal temperature, to 56 under the same load at 100°.

Cadmium is sometimes added to alloys of aluminium and zinc (1–40 % zinc) (patented by Bayliss and Clark, England) in the proportions of 0·001 to 10 respectively, an addition which confers great malleability, and facilitates working and stamping.

At other times, 0·5 % to 1 % of copper is added, or even 2 %, forming for aluminium-zinc alloys the soldering metal of the following composition:—

Aluminium .	88 %
Zinc . . .	10 %
Copper . .	2 %

(b) *Zinc-Aluminium Alloys.* Investigations on the alloys rich in zinc have been carried out by Léon Guillet and Victor Bernard.*

The following alloys, among others, were studied:—

(1) Binary zinc-aluminium alloys containing 1, 2, 3, or 5 % of aluminium.

(2) Ternary zinc-aluminium-copper alloys containing 2 % of aluminium and 2, 4, 6, or 8 % of copper; 4 % of aluminium and 2, 4, 6, or 8 % copper; 8 % of aluminium and 4 % of copper (German type of alloy).

The following results were obtained:—

(1) The cast alloys are of no value, the Elongation and Shock Resistance being approximately zero.

(2) The rolled alloys have low elongations and almost no Shock Resistance.

Extruded alloys generally have considerably increased elongations. This extrusion gave the following properties for the alloy containing 8 % of copper and 4 % of aluminium:—

Tensile Strength = 30 to 31 kg. per sq. mm. (19·05–19·68 tons per sq. in.)
% Elongation = 27–29
Shock Resistance = 2 kg. m. per sq. cm.

This is the most interesting of the zinc-aluminium alloys, but its Shock Resistance is very low.

* "Revue de Métallurgie," Sept.-Oct., 1918.

(2) ALUMINIUM-TIN ALLOYS.

The alloy, containing 3 % of tin, having a density 3·25, should be mentioned, as it is very suitable for casting.

Tin is frequently added in foundry practice, in order to facilitate the casting of alloys.

(3) ALLOYS OF ALUMINIUM AND MAGNESIUM.

It is clear that these alloys, from the point of view of lightness, are more important the more magnesium (density : 1·75) they contain.

(a) *Aluminium-Magnesium Alloys.* Magnalium, which contains 5–25 % of magnesium, has, for an average content of magnesium, a density of about 2·80 in the cast state.

MECHANICAL PROPERTIES OF ALUMINIUM-MAGNESIUM ALLOYS.

Jean Escard, in the work just quoted, gives the following values for alloys containing 2 % and 10 % of magnesium :—

Magnesium	Treatment	Tensile Strength		Elongation
		Kg./mm.²	Tons/in.²	%
2 %	Sand cast . . .	12·6	8·00	3
	Cast and rapidly cooled .	20·1	12·76	2
	Cast and quenched .	28·1	17·84	1
10 %	Sand cast . . .	15	9·52	2·4
	Cast and rapidly cooled .	23·6	14·99	3·4
	Cast and quenched .	43	27·30	4·2

The effect of quenching on alloys containing magnesium is marked, but we shall discuss this more fully in connection with the alloys of the second group (light alloys of great strength). A very small quantity of magnesium (0·5 to 1 %) is sufficient to increase the hardness after quenching in a most remarkable manner; the presence of 30 % to 50 % of magnesium renders the alloy hard and brittle.

(b) *Magnesium-Aluminium Alloys.* The magnesium-aluminium alloys, that is to say, alloys rich in magnesium, have been worked out by the Germans during the war, and the Zeppelin L 49, brought down at Bourbonne, possessed several parts made of similar alloys. The alloy would be of the type "Elecktron," known before the war, whose density is 1·8, and whose conductivity is of the same order as that of zinc; it contains 90–92 % of magnesium.

These alloys are very difficult to roll, and generally contain numerous holes and flaws.

The alloy containing 90 % of magnesium and 10 % of aluminium possesses the following properties, as cast :—

Elastic Limit	=8 kg. per sq. mm. (5·08 tons per sq. in.)
Tensile Strength	=11 kg. per sq. mm. (6·98 tons per sq. in.)
% Elongation	=1
Shock Resistance	=zero

Their most striking property is lightness, and they should not be overlooked by aviation authorities, who should take an interest in perfecting their manufacture.

Micrography of Casting Alloys of Aluminium.

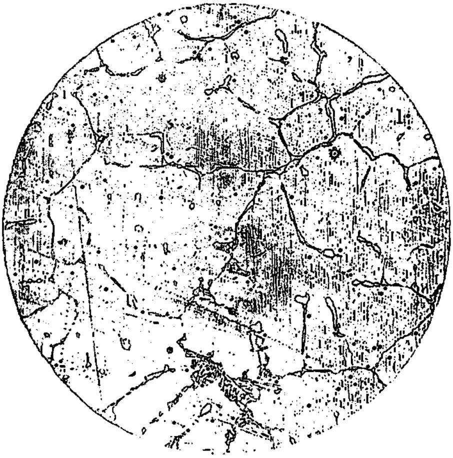
The five photographs in Plates III and IIIA show the micrographic appearance of the five casting alloys of aluminium that have been studied.

The first three refer to aluminium-copper alloys. These alloys contain the constituent η (this being, as we have seen, pure aluminium or a solid solution of copper and aluminium with a very low content of copper) plus the eutectic ($CuAl_2+\eta$).

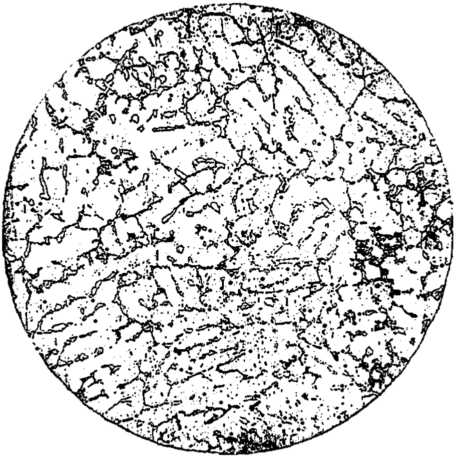
Photograph 1, Plate III, referring to the alloy containing 4 % of copper, shows solution η almost pure. Photographs 2 and 3, Plate III, referring to alloys containing 8 % and 12 % of copper respectively, show, to a slight extent, the eutectic previously described.

Photographs 4 and 5, Plate IIIA, refer to the ternary and quaternary alloys containing about 3 % and 11 % of copper respectively.

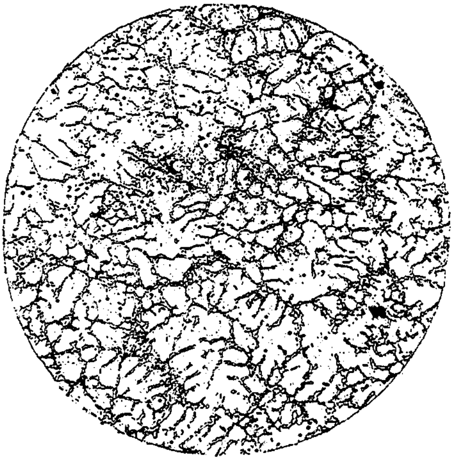
PLATE III.



PHOTOGRAPH 1.
Copper, 4 % ; Aluminium, 96 %.



PHOTOGRAPH 2.
Copper, 8 % ; Aluminium, 92 %.



PHOTOGRAPH 3.
Copper, 12 % ; Aluminium, 88 %.

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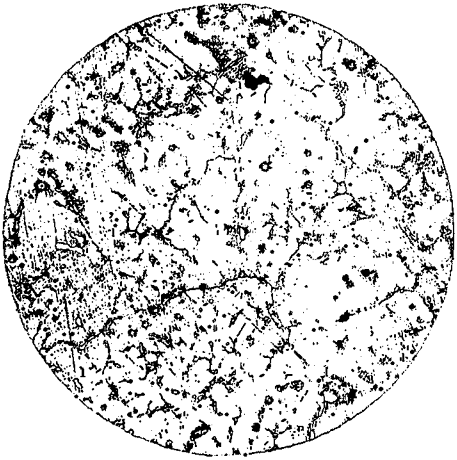
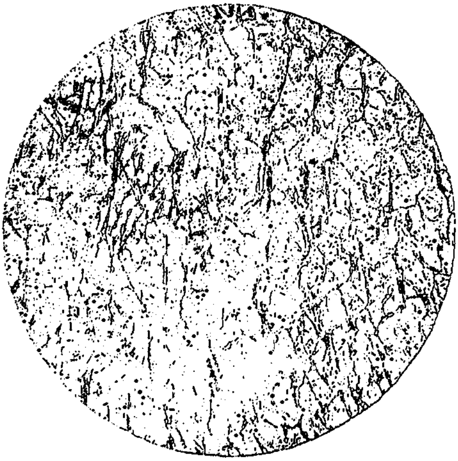
PLATE IIIA.



PHOTOGRAPH 4.
Copper, 3 %; Zinc, 12 %;
Aluminium, 85 %.



PHOTOGRAPH 5.
Copper, 11 %; Tin, 3 %; Nickel, 1 %;
Aluminium, 85 %.

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PART IV

LIGHT ALLOYS OF GREAT STRENGTH

THE group of light alloys of great strength comprises complex alloys containing copper, magnesium, manganese, and zinc, in addition to the aluminium; iron, silicon, and alumina are present as impurities, having been introduced with the aluminium.

These alloys have, as a rule, the following typical compositions :—

ALUMINIUM-COPPER-MAGNESIUM ALLOYS.

Copper	3·5–4 %
Magnesium	about 0·5 %
Manganese	0·5–1 %
Aluminium and impurities	(difference)

ALUMINIUM-COPPER-ZINC-MAGNESIUM ALLOY.

Copper	2·5–3 %
Zinc	1·5–3 %
Magnesium	0·5 %
Manganese	0·5–1 %
Aluminium and impurities	(difference)

The remarkable property of hardening after cooling, which these alloys possess, is due to the presence of the magnesium, or of the magnesium and zinc. This hardening is more pronounced as the cooling is more rapid. The mechanical properties, which the alloy possesses immediately after more or less rapid cooling, are changed completely after a certain interval of time. Without entering into a detailed discussion of the causes which bring about this transformation, we will study from a practical point of view, the results obtained by mechanical work and thermal treatment and from them deduce useful practical conclusions.

Tests have been carried out on light alloys, aluminium-copper-magnesium, having the average composition already given and corresponding with the light alloy known as duralumin.

A description of this work is given in the following form :—

Chapter I. (*a*) Variation in the mechanical properties (Tensile Strength, Elastic Limit, Elongation, Shock Resistance, and Hardness) with the amount of cold work. (*b*) Variation in these mechanical properties with annealing temperature (after cold work).

Chapter II. Quenching—Quenching Temperature, Rate of Cooling, and Ageing after Quenching.

Chapter III. Reannealing after Quenching.

Chapter IV. Cupping tests, after thermal treatment.

Chapter V. High temperature tests.

CHAPTER I

(*a*) Variation of the Mechanical Properties (Tensile Strength, Elastic Limit, Elongation, Shock Resistance, and Hardness) with the amount of Cold Work.

Test pieces were cut from sheets, 10 mm. thick, subjected to the required degree of cold work under the conditions already stated (see Fig. 38).

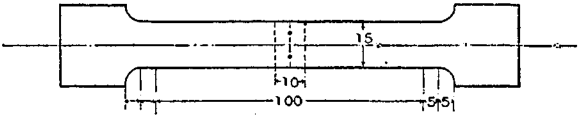


Fig. 38.—Tensile Test Piece (thick sheet).

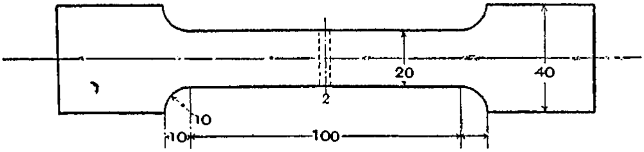


Fig. 39.—Tensile Test Piece (thin sheet).

Test pieces were also prepared from thin sheet (see Fig. 39).

This research was carried out upon metal which had been annealed in a bath of sodium nitrite and potassium nitrate at 450° C., and cooled in air. The reason for this initial treatment will be discussed later.

In its annealed condition the alloy possessed the following properties :—

	Tensile Strength Kg/mm²	Tensile Strength Tons/in²	Elastic Limit Kg/mm²	Elastic Limit Tons/in²	Elongation %	Shock Resistance Kg.m/cm²
Longitudinal	32	20·32	13	8·25	18	3
Transverse	26	16·51	12	7·62	10	2·5

The variations in these properties with the amount of cold work are shown in Figs. 40 and 41.

Discussion of Fig. 40 (test pieces cut longitudinally to direction of rolling).

Tensile Strength. This property decreases to a minimum at 15–20 % cold work, and then slowly increases.

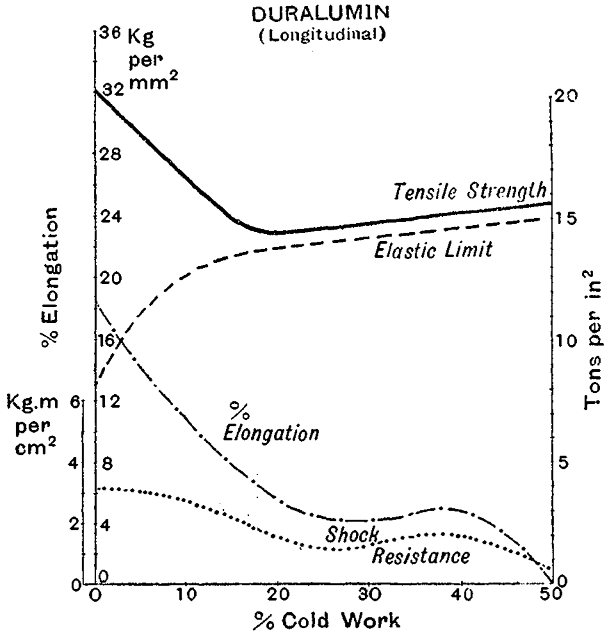


FIG. 40.—Variation in Mechanical Properties (Tensile and Impact) with Cold Work. Metal previously annealed at 450° and cooled in air.

Elastic Limit. This increases and, after 20 % cold work, is nearly equal to the Tensile Strength.

Elongation. This decreases very rapidly, falling from 18 % to 4 % as the cold work increases from 18 % to 20 %. The value remains constant from 20 % to 40 % cold work, and finally, at 50 % cold work, becomes extremely small (less than 1 %).

Shock Resistance. This falls from 3 kg. m. per sq. cm. to less than 1 kg. m. per sq. cm., while the cold work changes from 0 to 50 %

Fig. 41 (test pieces cut transversely to direction of rolling). The same general remarks apply, but there is an inflexion in the Elongation curve.

CONCLUSIONS.

For sheets of thickness 10 mm. or above, cold work to the amount of 50 % seems to be the maximum possible ; further

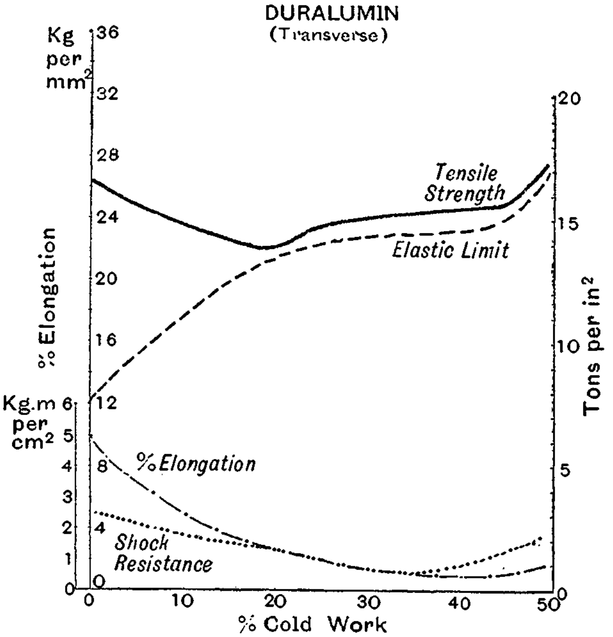


FIG. 41.—Variation in Mechanical Properties (Tensile and Impact) with Cold Work. Metal previously annealed at 450° and cooled in air.

work beyond this point leads to a cracking of the sheets. Moreover, a stronger plant is required than that usually employed for working this alloy—a point which does not arise in the working of thin sheets.

(*b*) VARIATION OF THESE MECHANICAL PROPERTIES WITH ANNEALING TEMPERATURE.

The material, upon which these tests were carried out, had been cold worked to the extent of 50 %, and test pieces were cut from it longitudinally and transversely to the direction of rolling. Up to 300° C. the metal was annealed

in oil and from 300° to 500° C. in the nitrate-nitrite bath. Since the rate of cooling has an effect, which will be discussed later, two standard rates have been used :—

(i) Cooling very slowly in the furnace or liquid bath itself (100 degrees per hour maximum rate).
(ii) Cooling in air.

The metal was allowed to age for eight days after cooling before being tested.

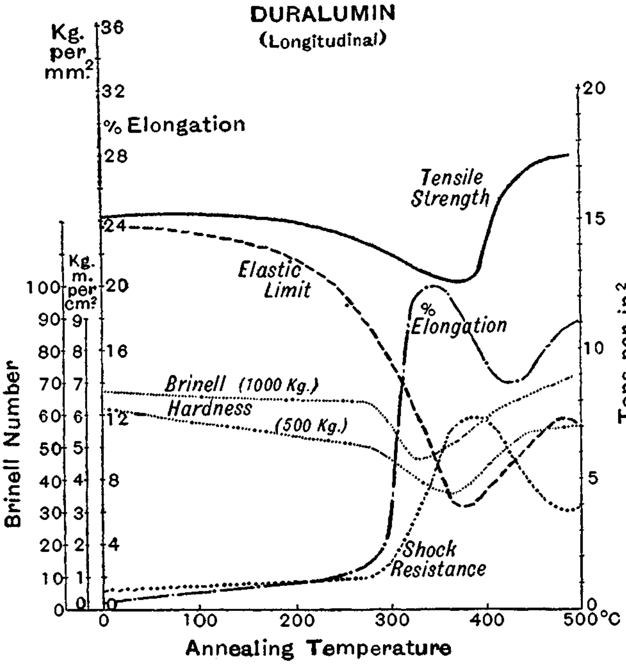


FIG. 42.—Variation in Mechanical Properties (Tensile, Hardness, and Impact) with Annealing Temperature. Metal subjected to 50 % Cold Work, annealed, and cooled very slowly.

The results are shown in Figs. 42, 43, 44, and 45.

Fig. 42,	Longitudinal,	Rate of cooling, (i) (furnace).
Fig. 43	,,	Rate of cooling, (ii) (air).
Fig. 44,	Transverse	Rate of cooling, (i) (furnace).
Fig. 45	,,	Rate of cooling, (ii) (air).

It is evident from these figures, that, whatever the rate of cooling and in whatever direction the test pieces are cut,

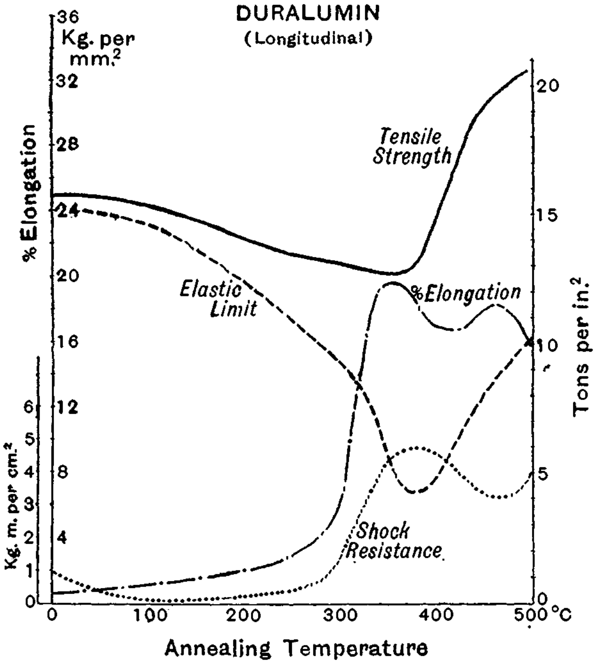


FIG. 43.—Variation in Mechanical Properties (Tensile and Impact) with Annealing Temperature. Metal subjected to 50 % Cold Work, annealed and cooled in air.

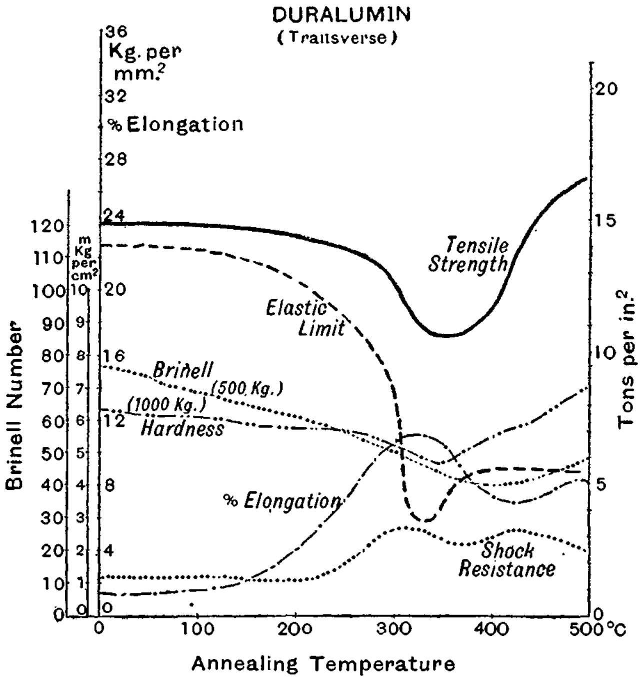


FIG. 44.—Variation in Mechanical Properties (Tensile, Hardness, and Impact) with Annealing Temperature. Metal subjected to 50 % Cold Work, annealed, and cooled very slowly.

there are two particularly interesting annealing temperatures, i.e. (1) 350°–375°, (2) 475°–500°.

The following table summarises the results obtained on the longitudinal test pieces for these temperatures, after 50 % cold work :—

Anneal		Tensile Strength		Elastic Limit		Elongation %	Shock Resistance Kg.m./cm.²
Temperature (degrees C.)	Rate of Cooling	Kg./mm.²	tons/in.²	Kg./mm.²	tons/in.²		
350	(i)	20	12·7	6	3·81	20	6
	(ii)	20	12·7	7	4·45	20	4–5
475	(i)	28	17·78	12	7·62	16	4
	(ii)	32	20·32	18	11·43	18	4

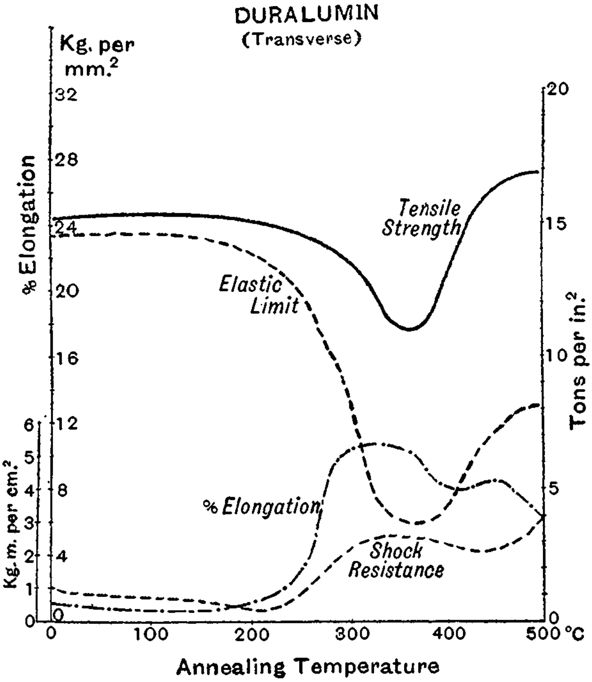


FIG. 45.—Variation in Mechanical Properties (Tensile and Impact) with Annealing Temperature. Metal subjected to 50 % Cold Work, annealed and cooled in air.

It is clear that these two temperatures correspond with maxima and minima of the tensile properties :—

350° anneal. First maxima of the Elongation and Shock Resistance.
Minima of Tensile Strength and Elastic Limit.

475° anneal. Second maxima of the Elongation and Shock Resistance.
Maxima of Tensile Strength and Elastic Limit.

The anneal at 350° C. may, therefore, be described as a softening anneal, producing maximum ductility in the metal. The anneal at 475° C. will be considered side by side with Quenching Phenomena in the following chapter.

CHAPTER II

QUENCHING

(*a*) Critical Points.

A research on the critical points of alloys of the duralumin type has been carried out by Chevenard, using a differential dilatometer.*

Fig. 46 shows the results obtained on comparing duralumin with pure aluminium.

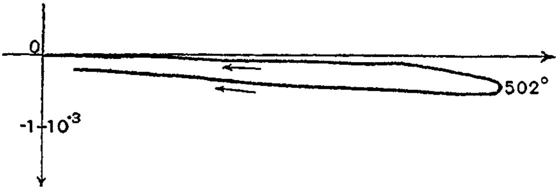


Fig. 46.—Duralumin compared with pure Aluminium, using Dilatometer.

The dilatometric method evidently gives no indication whatever of critical points in this alloy. On the expansion curve there is no sign of any definite irregularity.

Since there is, therefore, no a priori evidence marking out one limiting range of temperature, it is necessary to carry out a complete series of quenching experiments for all temperatures.

(*b*) Variation of Mechanical Properties with Quenching Temperature.

Omitting, for the present, the detailed discussion of the effect of time after quenching, the following procedure has been adopted.

Tensile and shock test pieces were cut longitudinally from

* For details of the use of this apparatus, *see* "L'Acier," by Lt.-Col. Grard (Berger-Levrault), 1919.

sheets of 10 mm. thickness, and possessed after rolling, i.e. in the cold-worked condition, the following properties:—

Tensile Strength . . .	24 kg./mm.^{2} or 15·24 tons/in.^{2}
Elastic Limit . . .	23 kg./mm.^{2} or 14·60 tons/in.^{2}
% Elongation . . .	5
Shock Resistance . .	2 kg.m./cm.^{2}

The test pieces were heated, preparatory to quenching, in a liquid nitrate-nitrite bath to the following temperatures: 300°, 350°, 400°, 450°, 500°, and 550° C.

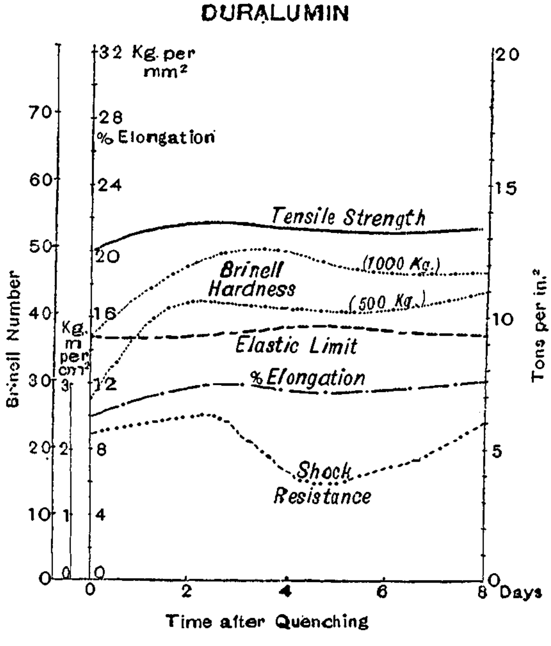


FIG. 47.—Variation in Mechanical Properties with Time after Quenching (from 300°).

Figs. 47–52 (inclusive) summarise the results obtained after quenching in water at 20° C.—which we will call rate of cooling (iii)—the tests being carried out

Immediately after quenching
48 hours ,, ,,
4 days ,, ,,
5 days ,, ,,
8 days ,, ,,

Fig. 53 shows the variation of mechanical properties with quenching temperature after a uniform ageing of eight days.

NOTES.

(1) *Influence of Time.*

The effect of the interval of time after quenching is noticeable from a temperature of 300° upwards, and is particularly marked above 400°.

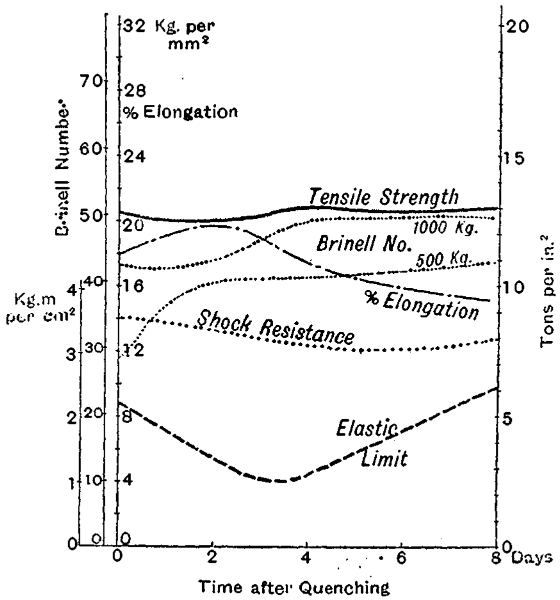


FIG. 48.—Variation in Mechanical Properties with Time after Quenching (from 350°).

(2) *Influence of Temperature.*

From 200° upwards, certain molecular changes take place and Fig. 53 reveals two particularly noticeable quenching temperatures, 350° and 475°, producing the following properties in the metal:—

Quenching from 350°

Tensile Strength . .	20 kg./mm.² or 12·7 tons/in.²
Elastic Limit . .	9 kg./mm.² or 5·61 tons/in.²
% Elongation . .	15
Shock Resistance . .	3 kg.m./cm.²

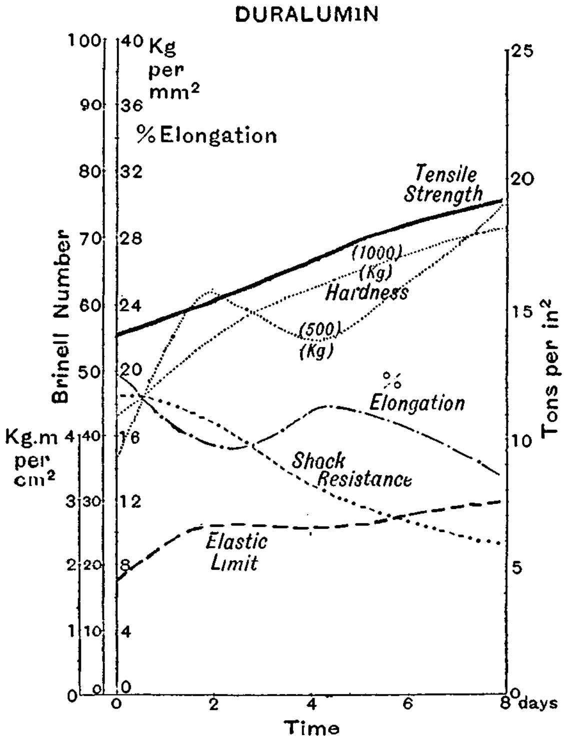


Fig. 49.—Variation in Mechanical Properties with Time after Quenching (from 400°).

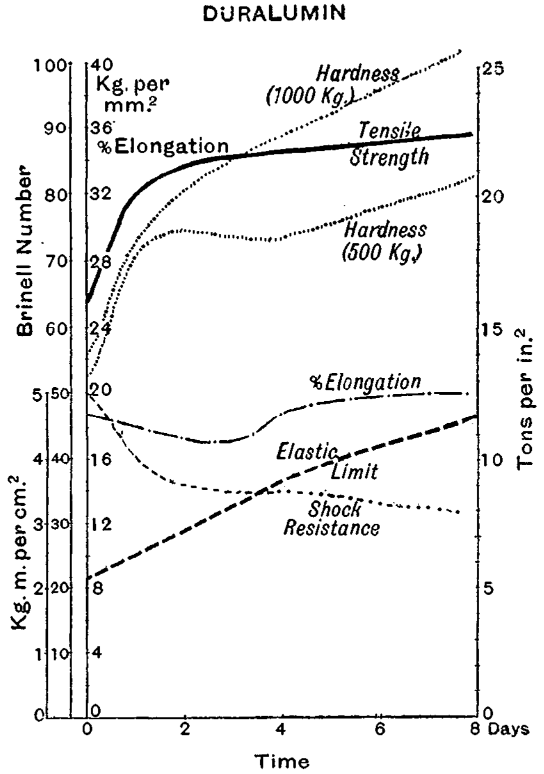


Fig. 50.—Variation in Mechanical Properties with Time after Quenching (from 450°).

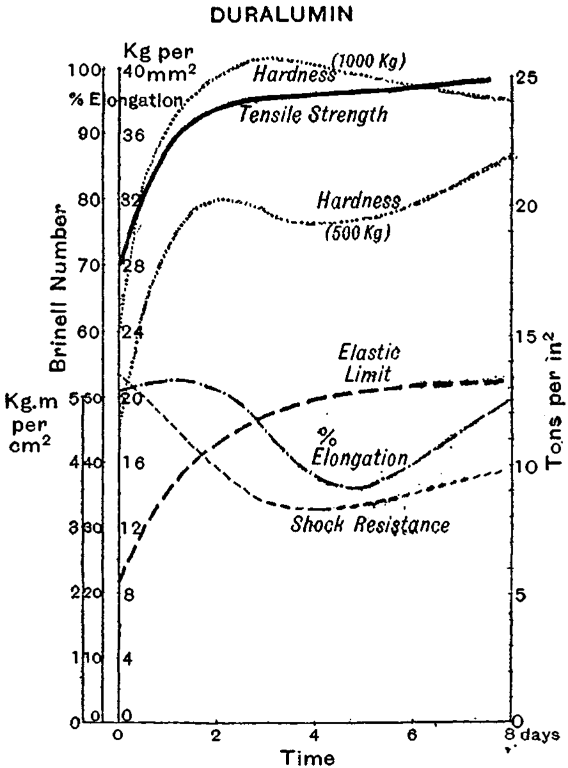


FIG. 51.—Variation in Mechanical Properties with Time after Quenching (from 500°).

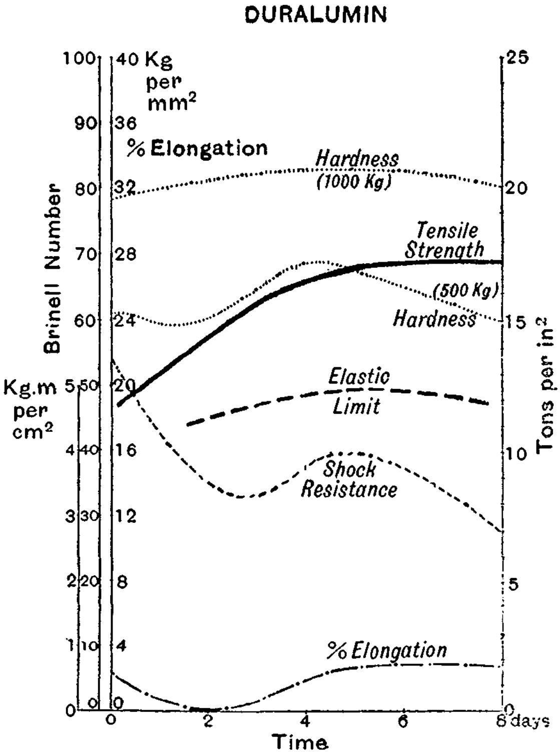


FIG. 52.—Variation in Mechanical Properties with Time after Quenching (from 550°).

Quenching from 475°

Tensile Strength . .	40 kg./mm.² or 25·4 tons/in.²
Elastic Limit . .	20 kg./mm.² or 12·7 tons/in.²
% Elongation . .	20
Shock Resistance . .	3·5 kg.m./cm.²

Remembering that quenching is nothing more than heating followed by very rapid cooling (rate iii), it is evident that, in

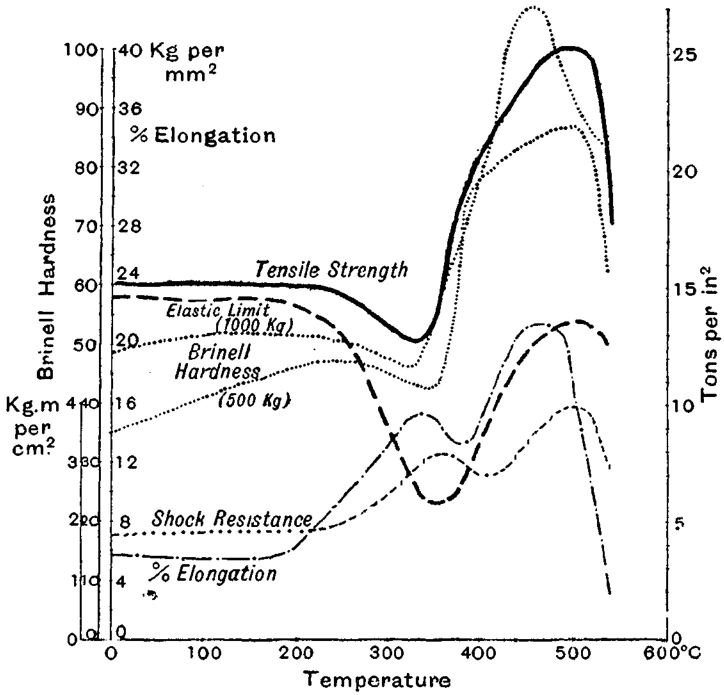


FIG. 53.—Variation in Mechanical Properties with Quenching Temperature (after 8 days).

this chapter and the preceding one, we have studied the variations of the worked alloy with the temperature of anneal after cold work, and with the rate of cooling following this anneal. The anneals at 350° and 475° have been pointed out as being especially interesting, whatever the rate of cooling.

The following table gives a summary of the results :—

Anneal		Tensile Strength		Elastic Limit		Elongation %	Shock Resistance Kg.m./cm.²
Temperature (degrees C.)	Rate of Cooling	Kg./mm.²	tons/in.²	Kg./mm.²	tons/in.²		
350°	(i) (100° p.h.)	20	12·7	6	3·81	20	6
	(ii) (air)	20	12·7	7	4·45	20	4–5
	(iii) (quenched in water)	20	12·7	9	5·61	15	3
475°	(i) (100° p.h.)	28	17·78	12	7·62	16	4
	(ii) (air)	32	20·32	18	11·43	18	4
	(iii) (quenched in water)	40	25·4	20	12·7	20	4

These two annealing temperatures correspond with a softening treatment and a final treatment.

The treatment which yields maximum softening consists in annealing at 350°, and cooling very slowly (rate (i), furnace). The final treatment, i.e. that which gives the alloy maximum strength, consists in annealing at 475° and cooling extremely rapidly (rate (iii), quenching in water). Other methods of treatment—annealing at 350° followed by more rapid cooling (rate (ii) or (iii)), or heating at 475° and cooling more slowly (rate (i) or (ii))—serve respectively to soften and harden the metal but to a less degree than the two treatments mentioned, which are, therefore, preferable.

Finally, Fig. 53 shows that quenching from above 550° produces a falling off in all properties. Quenching from 550° gives the following properties :—

Tensile Strength . . 27 kg./mm.^{2} or 17·14 tons/in.^{2}
Elastic Limit . . 19 kg./mm.^{2} or 12·06 tons/in.^{2}
% Elongation . . 2
Shock Resistance . . 2·5 kg.m./cm.^{2}

QUENCHING OF CAST DURALUMIN.

The properties of cast duralumin are as follows :—

Sand Cast.

Tensile Strength . (average) 11 kg./mm.^{2} or 6·98 tons/in.^{2}
% Elongation . approx. zero.
Shock Resistance . approx. zero.

Sand Cast, after Quenching.

Tensile Strength . (average) 14 kg./mm.^{2} or 8·89 tons/in.^{2}
% Elongation . approx. zero.
Shock Resistance . approx. zero.

Chill Cast.

Tensile Strength (average) .	10 kg./mm.² or 6·35 tons/in.²
% Elongation . . .	approx. zero.
Shock Resistance . .	approx. zero.

Chill Cast, after Quenching.

Tensile Strength (average) .	15 kg./mm.² or 9·52 tons/in.²
% Elongation . . .	approx. zero.
Shock Resistance . .	approx. zero.

It can be seen that unworked, cast duralumin is not affected by quenching.

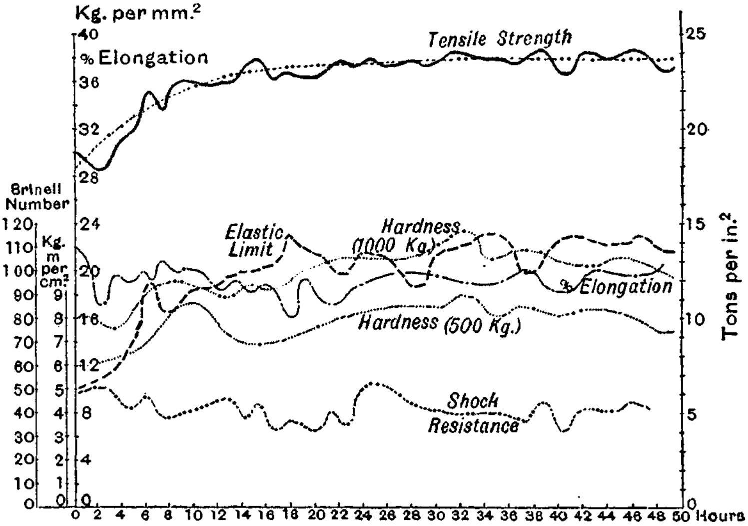


FIG. 54.—Variation in Mechanical Properties with Time after Quenching from 475° (during first 48 hours).

(c) VARIATION OF MECHANICAL PROPERTIES WITH DURATION OF TIME AFTER QUENCHING.

A constant temperature of quenching has been chosen, 475°. Four hundred bars of duralumin and the same number of shock test pieces were treated simultaneously, i.e. heated to 475° in the nitrate-nitrite bath and quenched in water. Tensi e tests, hardness tests, and shock tests were carried out under the following conditions :—

1st day .	6 an hour throughout the 24 hours.
2nd day .	4 an hour during the first 12 hours, 2 an hour during the second 12 hours.
3rd and 4th days .	2 an hour.
5th, 6th, 7th, and 8th days	2 every 2 hours.
For the following week .	2 every morning.
For the next fortnight .	2 a week.

These tests can be continued for a very long time on some test pieces kept in reserve.

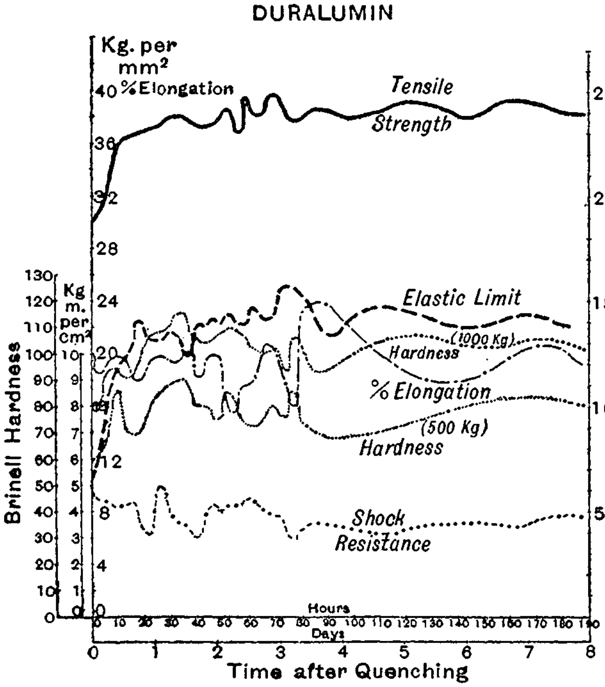


FIG. 55.—Variation in Mechanical Properties with Time after Quenching from 475° (during first 8 days).

VARIATION DURING THE FIRST EIGHT DAYS.

The results of the tests during the first twenty-four hours are accurately shown in Fig. 54.

Fig. 55 shows the results for the first eight days. Two distinct periods are noticeable :—

(*a*) First four days.
(*b*) Second four days.

(a) *First four days.*

The curves for this period are characterised by very marked oscillations, which cannot be attributed to experimental errors, and which evidently are due to notable molecular changes.

(b) *Second four days.*

During this period, the oscillations become less pronounced, and the wavy curves flatten out, tending to an equilibrium state.

GENERAL FORM OF CURVES.

The following conclusions may be drawn from a consideration of the general form of the curves lying most evenly through the points.

(1) *Tensile Strength.*

The Tensile Strength increases in an oscillatory manner, changing from 30 kg. per sq. mm. to 38 kg. per sq. mm. (19·05 tons/in^2 to 24·13 tons/in.^{2}) in the first four days. The variations during the last four days are included between the limits of 38 to 40 kg. per sq. mm. (24·13 to 25·40 tons per sq. in.). The most considerable increase occurs during the first ten hours when the value rises from 30 to 36 kg. per sq. mm. (19·06 to 22·86 tons per sq. in.).

(2) *Elastic Limit.*

This curve is of the same general form as that of the Tensile Strength, and in a similar manner increases from 10 to 23 kg. per sq. mm. (6·35 to 14·61 tons per sq. in.) in the first four days. The variations during the last four days, lie between the limits of 22 to 24 kg. per sq. mm. (13·97 to 15·24 tons per sq. in.). The greatest increase occurs during the first twenty-one hours when the value rises from 10 to 22 kg. per sq. mm. (6·35 to 13·97 tons per sq. in.).

(3) *Elongation.*

The Elongation oscillates very considerably during the first four days, but, at the end of eight days, the value is not appreciably altered. It varies about a mean value of 20 %.

(4) *Shock Resistance.*

The same remarks apply as for the Elongation.

(5) *Brinell Hardness.*

The curves of Hardness under a load of 1000 kg. and 500 kg. respectively are similar in form to those of Tensile Strength and Elastic Limit.

Brinell No. (1000 kg.) originally 80
,, after 24 hours 110
,, after 48 hours 100
,, after 8 days 100
(500 kg.) originally 61
,, after 24 hours 85
,, after 48 hours 80
,, after 8 days 75

The following table summarises these variations :—

	Elastic Limit		Tensile Strength		Elongation %	Shock Resistance Kg.m. cm.²
	Kg. mm.²	tons in.²	Kg. mm.²	tons in.²		
Immediately after quenching	10	6·35	30	19·05	20	4·5
Four days after quenching	22	13·97	38	24·13	22	3·4
Eight days after quenching	22	13·97	38	24·13	20	3·6

VARIATIONS AFTER EIGHT DAYS.

A further investigation of the variations in the properties of duralumin with the length of time after quenching can be carried out on the test pieces which were kept in reserve.

The tests carried out during the first three months do not reveal any important variations other than those which have been already noted at the end of eight days. It is advisable, however, to continue these tests for a very long period, and on a very considerable number of test pieces to minimise the effect of individual experimental errors, and to give a trustworthy value to the inferences drawn from the tests.

While these systematic tests are being carried out, we have attempted to find an alloy of high strength, prepared as long ago as possible, whose original properties had been accurately determined and whose date of manufacture was definitely known.

We approached the firm of Bréguet, who possess samples taken from the consignments from the works on dates definitely known. Tests had been carried out at the time of manufacture on test pieces taken from the samples. It must be noted that these samples have been kept in store and there is therefore no question of the alloy having been subjected to the strain of flight.

We could thus see how the alloy had behaved during storage. and investigate whether any ageing had taken place, i.e. an alteration of properties.

The following table summarises the results :—

Type of Sample	Date of Original test	Properties as determined in original tests					Date of Final tests	Properties as determined in final tests				
		Elastic Limit		Tensile Strength		Elongation %		Elastic Limit		Tensile Strength		Elongation %
		Kg. $mm.^2$	tons $in.^2$	Kg. $mm.^2$	tons $in.^2$			Kg. $mm.^2$	tons $in.^2$	Kg. $mm.^2$	tons $in.^2$	
Rectangular tube of 65/35 mm., thickness 0·2 mm.	1916	22	13·97	37	23·49	15	Oct. 7 1919	25·0	15·87	44·0	27·94	17·8
								23·3	14·80	42·6	27·05	11·05
								23·0	14·60	42·5	26·99	—
								26·6	16·89	44·0	27·94	17·08
Rectangular tube of 65/35 mm., thickness 0·25 mm	Mar. 1918	23·5	14·92	38	24·13	15	„	—	—	40	25·4	20
								25	15·87	40	25·4	17·3
								25	15·87	37·5	23·81	20
								25·3	16·07	37·8	24·0	20
Torpedo tube of 82/35 mm.	Oct. 1917	23·5	14·92	39	24·76	14	„	26·6	16·89	43·5	27·62	17
								26·6	16·89	43·5	27·62	15·2
Round tube of 75 mm. diam., thickness 0·2 mm.	June 1916	24	15·24	38	24·13	14	„	26	16·51	41	26·03	15·2
								27	17·14	44·6	28·32	15·2
Round tube of 55 mm. diam., thickness 0·2 mm.	Oct. 1916	23·5	14·92	38	24·13	14	„	29	18·41	41	26·03	15·2
								28·6	18·16	42·6	27·05	15·2
Round tube of 40 mm. diam., thickness 0·1 mm.	Oct. 1918	24	15·24	38	24·13	15	„	25	15·87	41	26·03	17·5
								27·5	17·46	40	25·4	17·5

This table shows that all the metal of this consignment has the following properties :—

Elastic Limit . (23 ± 1) kg. per sq. mm. $((14{\cdot}6 \pm {\cdot}63)$ tons per sq. in.)

Tensile Strength. (38 ± 1) kg. per sq. mm. $((24{\cdot}13 \pm {\cdot}63)$ tons per sq. in.)

% Elongation . $14{\cdot}5 \pm 0{\cdot}5$

After a lapse of time varying from one to three years, the properties lie between the following limits :—

Elastic Limit . (26 ± 3) kg. per sq. mm. $((16{\cdot}51 \pm 1{\cdot}9)$ tons per sq. in).

Tensile Strength. (41 ± 3) kg. per sq. mm. $((26{\cdot}03 \pm 1{\cdot}9)$ tons per sq. in).

% Elongation . 15–20.

With the exception of one test piece giving 11·05 % Elongation, an increase in the value of all the properties can be observed.

These particular tests, then, do not reveal any deterioration of the metal, but, on the contrary, a slight general improvement. In order to draw a reliable conclusion, we must await the final results of the methodical experiments now in hand—experiments in which the values of the original properties are reliable on account of the number of the tests and the particular care

taken in carrying them out. These experiments will allow us to find out definitely whether there is any gradual improvement in the properties.

Variation of the Time required to reach Equilibrium, with the Temperature after Quenching.

The preceding tests constitute an investigation of the time required to reach Equilibrium after quenching, in which the changes after quenching have been allowed to take place at the normal temperature. The effect of the temperature after quenching on the attainment of Equilibrium has been investigated by means of supplementary experiments.

The following temperatures were employed :—

— 20° C.
0° C.
+ 20° C.
+100° C.
150°
200°
250°
300°
350°

Immediately after quenching, test pieces were maintained at each of these temperatures for 1, 2, 3, 4, 5, and 6 hours respectively, i.e. some at —20°, others at 0°, other at +20°, etc.

Tensile tests were carried out after each of these periods of time, after warming up or cooling to air temperature.

The results can be summarised as follows :—

Temperature	−20°	After six hours there is no change in properties.
,,	0°	No change after six hours.
,,	+20°	After six hours the Tensile Strength has increased by 4 kg. per sq. mm. (2·54 tons per sq. in.) to the value 34 kg. per sq. mm. (21·6 tons per sq. in.).
,,	100°	After six hours the Tensile Strength has increased by 8 kg. per sq. mm. (5·08 tons per sq. in.) and become 38 kg. per sq. mm. (24·13 tons per sq. in.). All the properties have attained their mean normal values.

Temperature	150°	All the properties have attained their mean normal values after two hours.
,,	200° and above	The process is simply an anneal and the rate of cooling has a pronounced effect.
		The results obtained are strictly concordant with those drawn diagrammatically in Fig. 57 (variation of mechanical properties with temperature of reanneal after quenching from 475°).

From these tests the following conclusions may be drawn :—

Changes after quenching are retarded by low temperature.

They become more rapid as the temperature immediately after quenching is raised between the limits of 0° and 150°, temperatures above 150° causing, after similar cooling to air temperature, changes in the properties. If the alloy be immersed in boiling water, for example—a very practical procedure—Equilibrium is reached much more rapidly.

Immediately after quenching.
Tensile Strength =30 kg. per sq. mm. (19·05 tons per sq. in.)
Elastic Limit =10 kg. per sq. mm. (6·35 tons per sq. in.)
% Elongation =18

After immersion in boiling water for one hour after quenching.
Tensile Strength =35·5 kg. per sq. mm. (22·54 tons per sq. in.)
Elastic Limit =17·5 kg. per sq. mm. (11·10 tons per sq. in.)
% Elongation =20

After immersion in boiling water for two hours after quenching.
Tensile Strength =37 kg. per sq. mm. (23·49 tons per sq. in.)
Elastic Limit =18·5 kg. per sq. mm. (5·40 tons per sq. in.)
% Elongation =20

After six hours under these conditions.
Tensile Strength =37 kg. per sq. mm. (23·49 tons per sq. in.)
Elastic Limit =20 kg. per sq. mm. (12·7 tons per sq. in.)
% Elongation =20
Values which remain approximately unchanged after further immersion in boiling water.

Thus, by immersion in boiling water after quenching, Equilibrium is reached more rapidly—an effect which is of interest from the industrial point of view.

CHAPTER III

VARIATION OF MECHANICAL PROPERTIES WITH THE TEMPERATURES OF REANNEAL AFTER QUENCHING

THE metal, in every case quenched from 475°, was reannealed at a series of temperatures—every fifty degrees from the normal up to 500°—and cooled.

The three rates of cooling already defined were employed: rate (i), cooling very slowly in the bath; rate (ii), cooling in air; rate (iii), cooling by quenching in water.

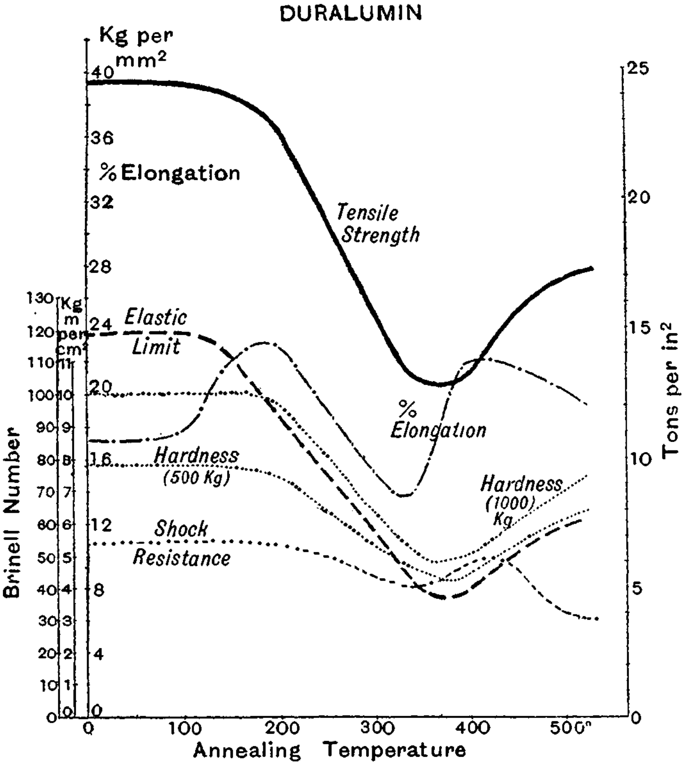


FIG. 56.—Variation in Mechanical Properties with Annealing Temperature. Metal quenched from 475°, reannealed, and cooled very slowly.

The results for the three rates of cooling are shown in Figs. 56, 57, and 58 respectively.

All the properties show a minimum at a temperature which varies with the rate of cooling as shown in the following table :—

Rate of Cooling	Temperature of Minimum	Values corresponding with the minimum					
		Tensile Strength		Elastic Limit		Elongation %	Shock Resistance
		Kg. mm.²	tons in.²	Kg. mm.²	tons in.²		Kg. m. cm.²
(i)	330°–360°	20	12·7	7	4·4	14	4·5
(ii)	290°–320°	25	15·87	11	6·98	14	5
(iii)	275°–300°	24	15·24	9	5·71	14	5

These minima do not afford any particular interest.

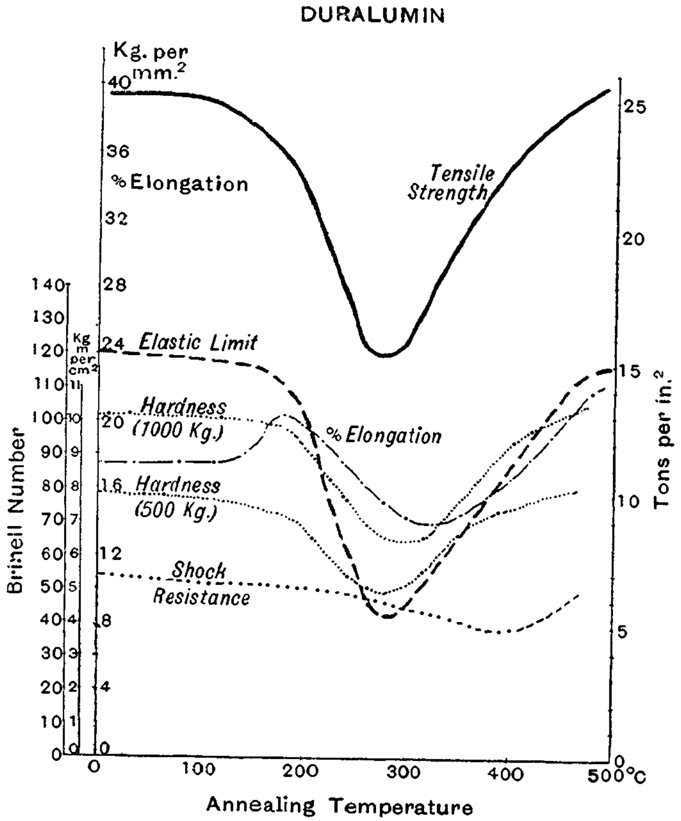


FIG. 57.—Variation in Mechanical Properties with Annealing Temperature. Metal quenched from 475°, reannealed, and cooled in air.

Fig. 56. Quenching from 475°, reannealing followed by very slow cooling (rate (i)).

The most interesting points on these curves correspond with the reannealing temperature 400°.

For this temperature :—

Tensile Strength =22 kg. per sq. mm. (13·97 tons per sq. in.)
Elastic Limit =7 kg. per sq. mm. (4·44 tons per sq. in.)
% Elongation =22
Shock Resistance=5 kg. m. per sq. cm.

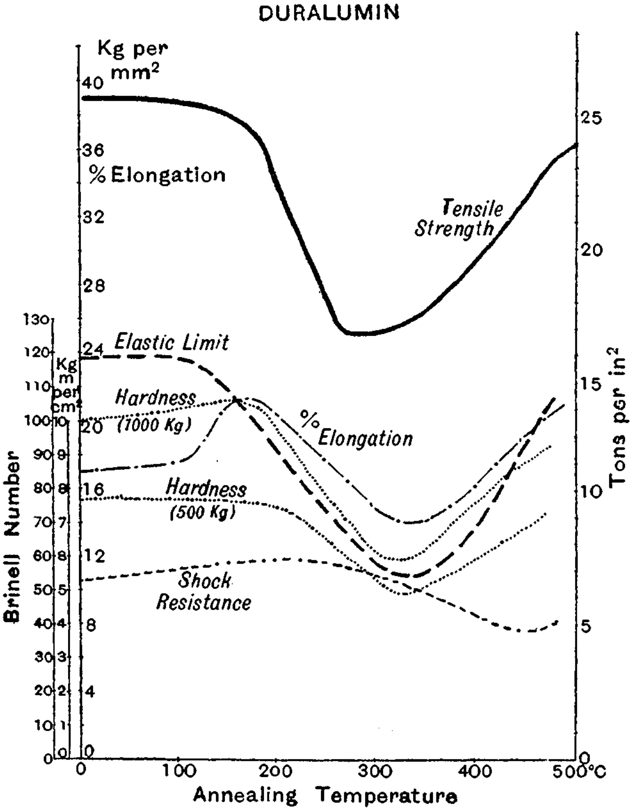


FIG. 58.—Variation in Mechanical Properties with Annealing Temperature. Metal quenched from 475°, reannealed, and quenched in water.

This is a softening treatment, giving values approximately equal to those produced by the softening process previously described but entailing a more complicated method of working.

Fig. 57. Quenching from 475°, reannealing, followed by cooling in air (rate (ii)).

No particular advantage.

Fig. 58. Quenching from 475°, reannealing and quenching in water (rate (iii)).

The most interesting values are those corresponding with the range of annealing temperatures 475°–500°.

This is simply a process of double quenching and gives the alloy the following properties :—

Tensile Strength	=40 kg. per sq. mm. (25·4 tons per sq. in.)
Elastic Limit	=23 kg. per sq. mm. (14·6 tons per sq. in.)
% Elongation	=22
Shock Resistance	=5 kg. m. per sq. cm.

It is clear from these values that a double quenching is superior to a single one. Two quenchings improve the Elastic Limit, the Elongation, and the Shock Resistance, and should therefore be employed if the maximum values of these properties are required in the finished metal.

CONCLUSION.

From the practical point of view, this type of light alloy can be subjected, after cold work, to three treatments :—

(1) Annealed at 350° and cooled very slowly (rate (i)), giving the most suitable intermediate state from the point of view of further mechanical work. This is the softening process.

(2) Annealed at 475° and quenched, yielding the hardened or final state.

(3) Annealed at 475°, quenched, reannealed at 475°–500°, and quenched again. This process—double quenching—yields the optimum final state.

CHAPTER IV

RESULTS OF CUPPING TESTS AFTER VARYING THERMAL TREATMENT

THE experimental methods were the same as those described already for the cupping tests on aluminium (page 41).

The circles to be tested were taken from sheets, 2 mm. thick, having been cold worked to the extent of 40 %.

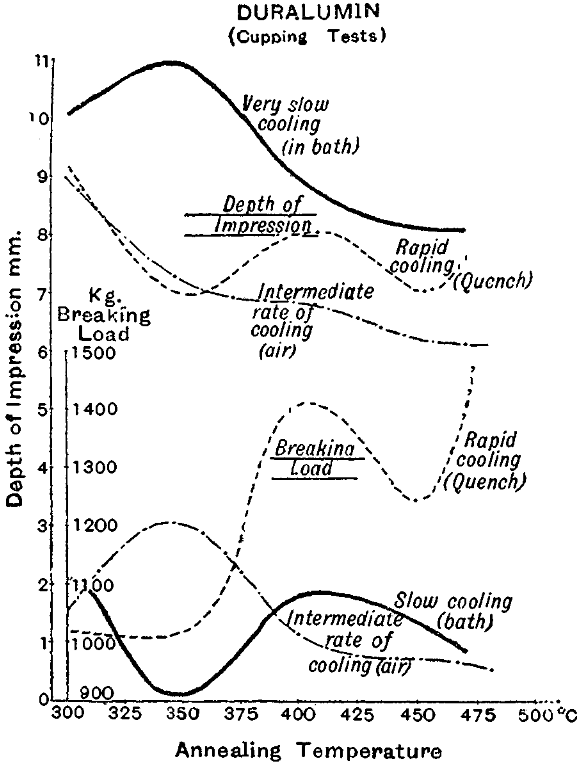


FIG. 59.—Variation in Breaking Load and Depth of Impression with Annealing Temperature. Anneal followed by cooling at varying rates :

———————— very slow.
— — — — — — — — cooling in air (intermediate rate).
—— . —— . —— cooling in water (quenching ; very rapid).

The following temperatures of annealing after cold work and the following rates of cooling have been employed :—

Temperature of anneal: 300°, 350°, 400°, 450°, 475°.
Rates of cooling : (i), (ii), and (iii) (as previously defined).

Fifteen circles were heated at each of the above temperatures, and of these, five were cooled very slowly (rate (i)), five in air (rate (ii)), and five quenched (rate (iii)).

The results of the tests are shown in Fig. 59, representing the curves for the breaking loads and for the depths of impression corresponding with the different rates of cooling, plotted against varying annealing temperature.

The general shape of these curves shows very clearly the remarkable results of annealing at 350° and cooling very slowly (rate (i)). This treatment gives to the alloy the maximum ductility, and in this molecular state the maximum depth of impression is produced.

These cupping tests confirm the preceding tests, and we can conclude that annealing at 350°, after cold work, followed by very slow cooling (rate (i)), is the optimum treatment for softening the metal, i.e. for producing maximum ductility and maximum malleability.

Certain cupping tests have been carried out on sheets possessing different degrees of cold work (20–100 %) under the same experimental conditions, i.e. annealing at the specified temperatures and cooling according to the three rates of cooling mentioned.

The same conclusions were arrived at as in the case of 40 % cold work. Furthermore, the final values, after annealing at 350° or at 475°, followed by variable rates of cooling, vary directly with the amount of cold work. The maximum malleability is thus obtained, for thin sheets, by cold working to the amount of 100 %, and annealing at 350° followed by very slow cooling.

CHAPTER V

HARDNESS TESTS AT HIGH TEMPERATURES

HARDNESS determinations were made at every fifty degrees up to 600° on sixty cylindrical test pieces, 20 mm. long and 20 mm. in diameter. The pressure used was 500 kg.

The results are shown in Fig. 60, which should be considered side by side with those obtained under the same conditions for aluminium and casting alloys.

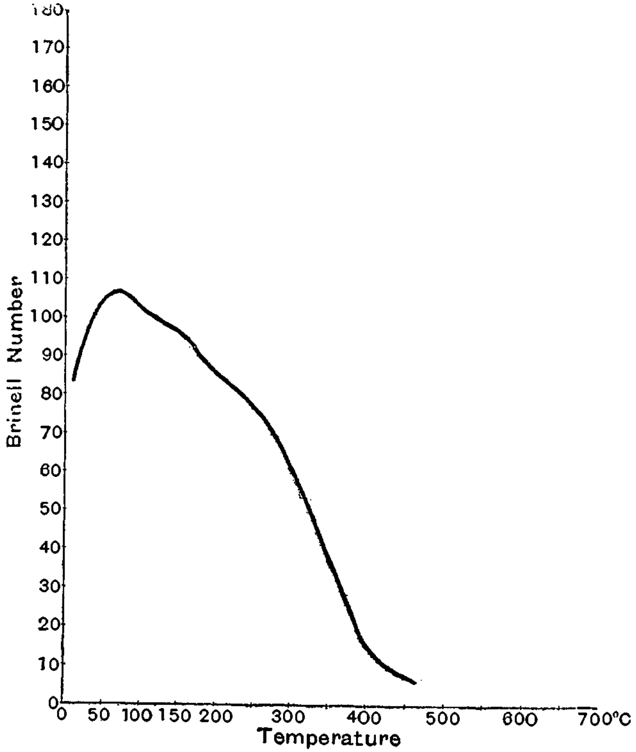


FIG. 60.—High Temperature Hardness Tests (500 Kg.) on Duralumin quenched from 475°.

PART V

THE CUPRO-ALUMINIUMS OR ALUMINIUM BRONZES

THE cupro-aluminiums considered, from an industrial standpoint, are those in which the respective amounts of the constituents are limited to the part of Curry's diagram lying between 88 % and 92 % of copper, or 12 % and 8 % of aluminium, though the presence of other constituents, such as manganese, iron, or nickel, may cause variations in these amounts.

The typical alloy, i.e. the alloy containing 90 % of copper and 10 % of aluminium, was studied in a very thorough manner by H. St. Claire Deville, more than sixty years ago, at which time it was still a precious metal, whose cost price was about 32 francs per kilogramme (11s. 9d. per lb.).

Numerous investigations have been made since that of St. Claire Deville, particularly by H. Le Chatelier, Campbell and Mathews, Guillet, Breuil, Gwyer, Carpenter and Edwards, Curry, Rosenhain, and afterwards Portevin and Arnon.

We only intend to discuss the particular results obtained for three special, clearly defined alloys, referring for questions of a general nature to the notable works mentioned above. These results show the uses to which these alloys can be put, and the properties they may possess.

These alloys fall into the following classes :—

- Type I. Alloy containing 90 % of copper and 10 % of aluminium.
- Type II. Alloy containing 89 % of copper, 1 % of manganese, and 10 % of aluminium.
- Type III. Alloy containing 81 % of copper, 4 % of nickel, 4 % of iron, and 11 % of aluminium.

We shall summarise the results of this investigation in the following manner :—

- Chapter I. General properties of the cupro-aluminiums.
- Chapter II. Mechanical properties.
- Chapter III. Micrography.

CHAPTER I

GENERAL PROPERTIES OF THE CUPRO-ALUMINIUMS

Chemical Properties.

These alloys are sufficiently resistant to the chemical action of liquids, especially sea water.

They are not oxidised at high temperatures, which renders them particularly suitable for the direct production of finished and accurate stampings.

Physical Properties.

Colour. The alloys are yellow or slightly green, and capable of taking a high polish.

Density. This varies with the percentage of aluminium. For the 90/10 alloy, it is about 7·5 (Density of copper =8·8
,, aluminium =2·6)
Aluminium bronze thus has an advantage, from the point of view of weight, over 60/40 brass, whose density is about 8·4, and which is employed for some of the same purposes.

Wear and Abrasion. Cupro-aluminiums or aluminium bronzes have a mineralogical hardness, which is retained at relatively high temperatures, as we shall see later. Their sclerometric or " scratch " hardness is great. As regards wear, the advantages of cupro-aluminium are unquestionable. From the point of view of abrasion, cupro-aluminium possesses valuable qualities, and its coefficient of friction is low—it possesses properties approaching those of antifriction metals.

Specific Resistance. As soon as a little aluminium is added to copper, its resistivity is increased. The Specific Resistance of cupro-aluminiums is shown in the following table, which summarises the work of Pecheux. It is expressed in microhms per cm. cube.

Aluminium. %	*Value of Specific Resistance at a Temperature* t.
3	$Rt = 8{\cdot}26(1+0{\cdot}00102t+0{\cdot}000003t^2)$
5	$Rt = 10{\cdot}21(1+0{\cdot}00070t+0{\cdot}000002t^2)$
6	$Rt = 11{\cdot}62(1+0{\cdot}00055t+0{\cdot}000002t^2)$
7·5	$Rt = 13{\cdot}62(1+0{\cdot}00036t+0{\cdot}000001t^2)$
10	$Rt = 12{\cdot}61(1+0{\cdot}00032t+0{\cdot}000002t^2)$
94	$Rt = 3{\cdot}10(1+0{\cdot}00038t+0{\cdot}000003t^2)$

Electric Permeability. Very low. Cupro·aluminiums may be considered to be almost impermeable and non·magnetic.

Foundry Difficulties. The great difficulty lies in obtaining sound ingots, the obstacles being the large contraction of the cupro·aluminium, the liberation of gases at the moment of solidification, and the formation of alumina which is difficult to remove. This question of casting has been the subject of investigation. The use of large runners feeding the ingot, and the stirring and skimming of the surfaces is a remedy, which has the disadvantage of greatly increasing the cost price. The economic production with small runners and the avoidance of skimming can be carried out to-day by means of the device for casting without oxidation—Durville's method.

Suitability for Forging. Aluminium bronzes can be forged very easily at a temperature of 900°. There is, therefore, a very much greater scope for forging in a single heating than in the case of the 60/40 brasses, which have only a limited range of temperature, about 600°, at which forging is possible. Furthermore, with certain of these alloys, as we shall see, it is possible to obtain after treatment results distinctly superior to those of the forgeable brasses, as regards Tensile Strength and Elastic Limit as well as Elongation.

Suitability for Casting. The malleability of aluminium bronzes at high temperatures and their freedom from oxidation makes them suitable for castings, particularly in metallic moulds. The contraction of the alloys constitutes a difficulty which can be overcome by the skill of the founder and a suitable arrangement of runners.

Nevertheless, the suitability for forging and stamping seems to be the outstanding characteristic of cupro·aluminiums, and should be made use of in the majority of cases.

Use. The above account describes the forgeability, freedom from oxidation, electric impermeability, and the resistance to wear and abrasion, which result in the use of the alloy for the manufacture of pressed articles, of wire for springs and electrical resistances, and of electrical apparatus.

CHAPTER II

MECHANICAL PROPERTIES

THE mechanical tests carried out were :—

(1) Tensile tests,
(2) Shock tests,
(3) Hardness tests,

and were preceded by an investigation of the critical points by the dilatometric method.

(1) *Tensile Tests.* These tests were carried out on cylindrical bars, 13·8 mm. in diameter, and shaped as in Fig. 61.

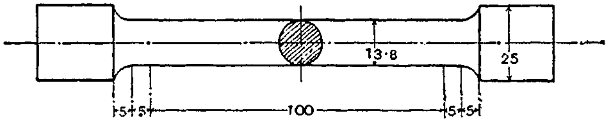


FIG. 61.—Tensile Test Piece (Round Bars).

(2) *Shock Tests.* These were carried out on test pieces of $10 \times 10 \times 53$ mm. with a 2·mm. notch.

(3) *Hardness Tests.* These were carried out at gradually increasing, high, temperatures, under a load of 500 kg., on cylinders 2 cm. in diameter and 2 cm. high, using a ball 10 mm. in diameter.

The test pieces were taken from forged or cast bars ; liquid baths were employed to heat the test pieces, and the temperature accurately regulated.

Scheme of Work. The investigations were carried out according to the following general scheme for each type of alloy considered, with simplifications for certain types :—

(*a*) Preliminary chemical analysis.

(*b*) Determination of curve of critical points.

(*c*) Investigation of the variation in mechanical properties with temperature of anneal after casting or forging

(d) Investigation of the variation in mechanical properties with the quenching temperature.

(e) Investigation of the variation in mechanical properties with temperature of reanneal subsequent to quenching from different temperatures.

(f) Hardness tests at ordinary and high temperatures.

I. Type I

90 % Copper—10 % Aluminium

(a) Chemical Analysis.

Copper	89·15
Aluminium . . .	10·10
Manganese . . .	0·30
Iron	0·25
Nickel	nil
Zinc	nil
Lead	nil
Tin	nil
Difference . . .	0·2
	100·0

(b) Determination of Critical Points.

These critical points have been investigated by Chevenard, and the results are shown in the following diagrams.

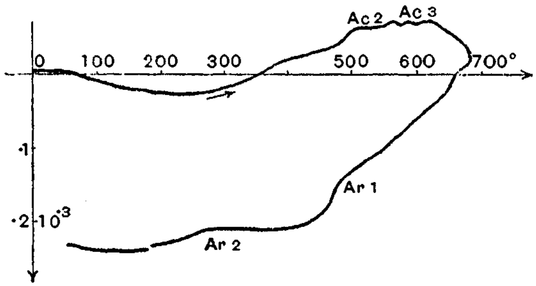


Fig. 62.—Aluminium Bronze, Type I.

The expansion curves show, on heating, three breaks, Ac_1, Ac_2, Ac_3, and on cooling again two breaks, Ar_1 and Ar_2 (see Fig. 62). Whenever the alloy is heated above the point Ac_3, similar phenomena are observed on cooling again ; the position of the points Ar_1, Ar_2, appear hardly to depend upon the rate

of cooling (see Figs. 63 and 64). In Fig. 64, the mean rate of cooling is half that represented in Fig. 63.

If the temperature does not reach Ac_3 (Fig. 65), the curve of cooling is without any peculiarity.

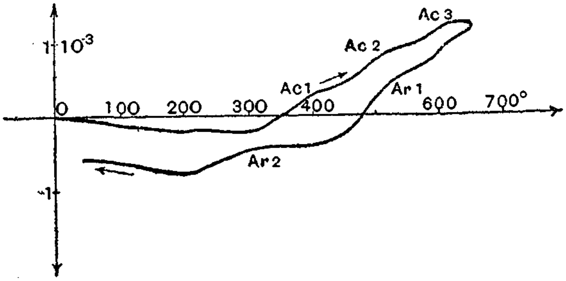


FIG. 63.—Aluminium Bronze, Type I. Allowod to cool in Furnace.

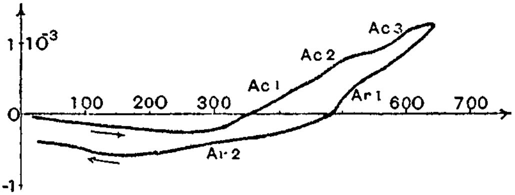


FIG. 64.—Aluminium Bronze, Type I. Slow cooling.

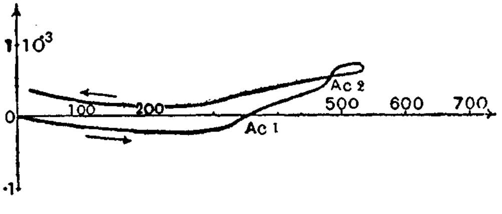


FIG. 65.—Aluminium Bronze, Type I. Temperature not exceeding Ac_3.

(c) VARIATION IN THE MECHANICAL PROPERTIES OF CUPRO-ALUMINIUM (TYPE I), TENSILE AND IMPACT, WITH THE ANNEALING TEMPERATURE.

(c_1) *Alloy as Cast.*

The variation in these properties are summarised in Fig. 66. The test pieces were cooled in air after heating. As cast, cupro-aluminium (Type I) possesses the following properties :—

Tensile Strength =40 kg. per sq. mm. (25·4 tons per sq. in.)
Elastic Limit =26 kg. per sq. mm. (16·51 tons per sq. in.)
% Elongation =10
Shock Resistance= 1 kg. m. per sq. cm.

Annealing has a particularly advantageous effect on the Elongation and Shock Resistance, so that after annealing at about 800°, the properties have the following values :—

Tensile Strength =52 kg. per sq. mm. (33·02 tons per sq. in.)
Elastic Limit =24 kg. per sq. mm. (15·24 tons per sq. in.)
% Elongation =22
Shock Resistance=5 kg. m. per sq. cm.

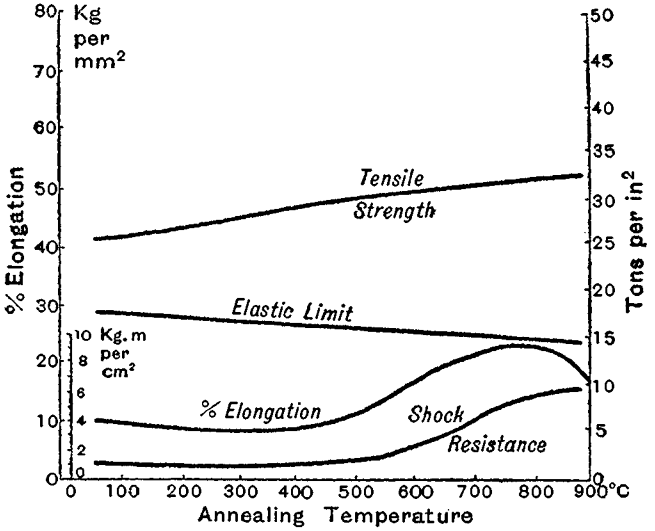


Fig. 66.—Variation in Mechanical Properties (Tensile and Impact) with Annealing Temperature. Cast Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

(c_2) *Alloy as Forged.*

The variations in the properties are summarised in Fig. 67. In the forged state, cupro-aluminium (Type I) has the following properties :—

Tensile Strength =56 kg. per sq. mm. (35·56 tons per sq. in.)
Elastic Limit =32 kg. per sq. mm. (20·32 tons per sq. in.)
% Elongation =10
Shock Resistance=2 to 3 kg. m. per sq. cm.

Annealing at 850° especially improves the Shock Resistance and Elongation, whilst lowering the Elastic Limit :—

Tensile Strength =55 kg. per sq. mm. (34·92 tons per sq. in.)
Elastic Limit =22 kg. per sq. mm. (13·97 tons per sq. in.)
% Elongation =24
Shock Resistance = 6 kg. m. per sq. cm.

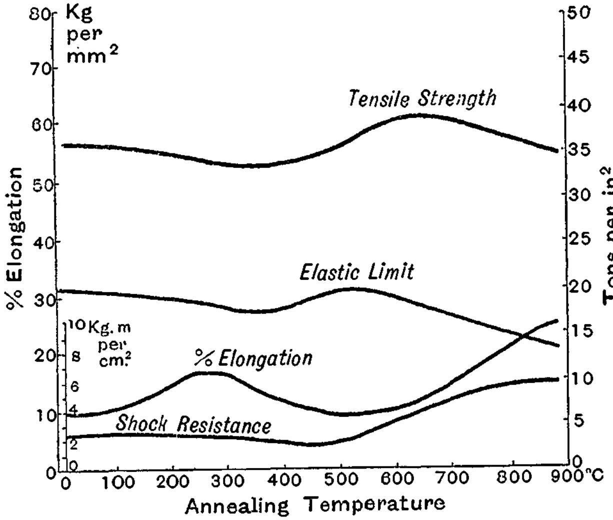


Fig. 67.—Variation in Mechanical Properties (Tensile and Impact) with Annealing Temperature. Forged Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

(*d*) Variation in the Mechanical Properties, Tensile and Impact, with Quenching Temperature.

(d_1) *Alloy as Cast.*

The variations in the properties are summarised in Fig. 68. The maximum Shock Resistance and Elongation are obtained by quenching from 600°, which results in the following properties in the cast metal :—

Tensile Strength =56 kg. per sq. mm. (35·56 tons per sq. in.)
Elastic Limit =26 kg. per sq. mm. (16·51 tons per sq. in.)
% Elongation =12
Shock Resistance = 6 kg. m. per sq. cm.

—a distinct improvement on the original cast alloy.

(d_2) *Alloy as Forged.*

The variations in the properties are summarised in Fig. 69.

Quenching from 500° has little effect on this cupro-aluminium, which retains approximately the properties that it possessed in the forged state. The effect of quenching from above 500° is distinctly noticeable.

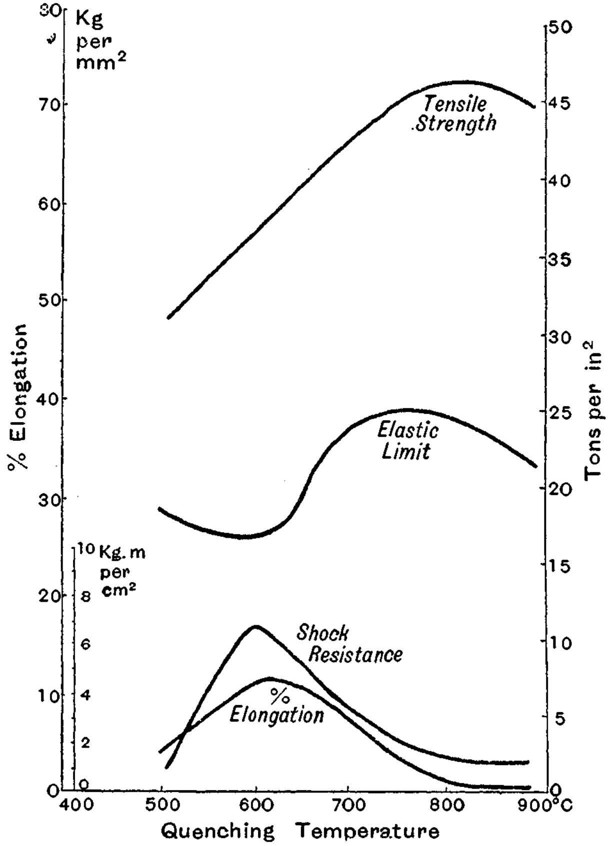


FIG. 68.—Variation in Mechanical Properties (Tensile and Impact) with Quenching Temperature. Cast Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

After quenching from 650°—

Tensile Strength = 64 kg. per sq. mm. (40·64 tons per sq. in.)
Elastic Limit = 32 kg. per sq. mm. (20·32 tons per sq. in.)
% Elongation = 16
Shock Resistance = 8 kg. m. per sq. cm.

This is approximately the maximum for Shock Resistance and Elongation, all the properties being superior to those of the quenched, cast, alloy.

Quenched from above 650°, the Elongation and Shock Re-

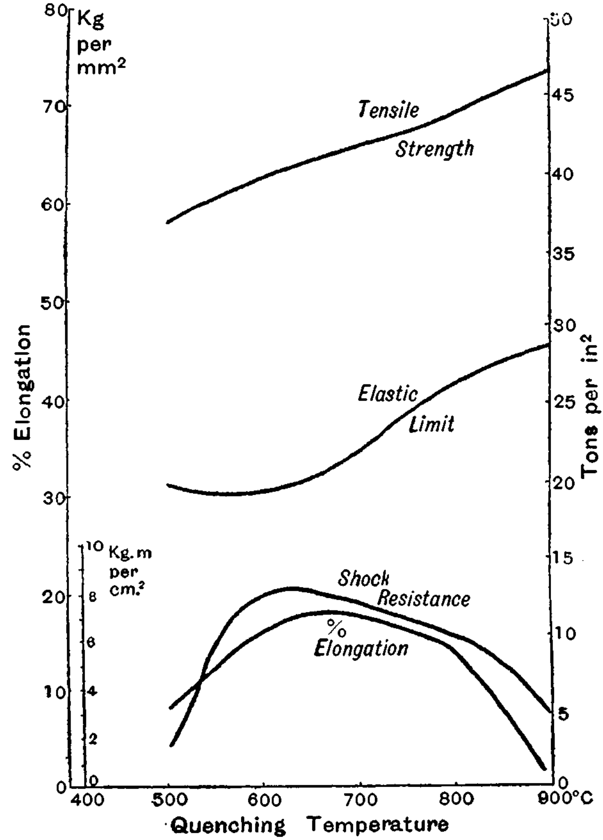


Fig. 69.—Variation in Mechanical Properties (Tensile and Impact) with Quenching Temperature. Forged Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

sistance decrease while the Tensile Strength and Elastic Limit continue to increase, so that, after quenching from 900°, they have the following values :—

Tensile Strength = 72 kg. per sq. mm. (45·72 tons per sq. in.)
Elastic Limit = 44 kg. per sq. mm. (27·94 tons per sq. in.)

(*e*) VARIATION IN THE MECHANICAL PROPERTIES, TENSILE AND IMPACT, WITH TEMPERATURE OF REANNEAL SUBSEQUENT TO QUENCHING THE FORGED ALLOY.

The following quenching temperatures were investigated :—

700°
800°
900°

For each of these, investigation was made as to the effect of reannealing at every fifty degrees from 300° to a temperature one hundred degrees below the quenching temperature.

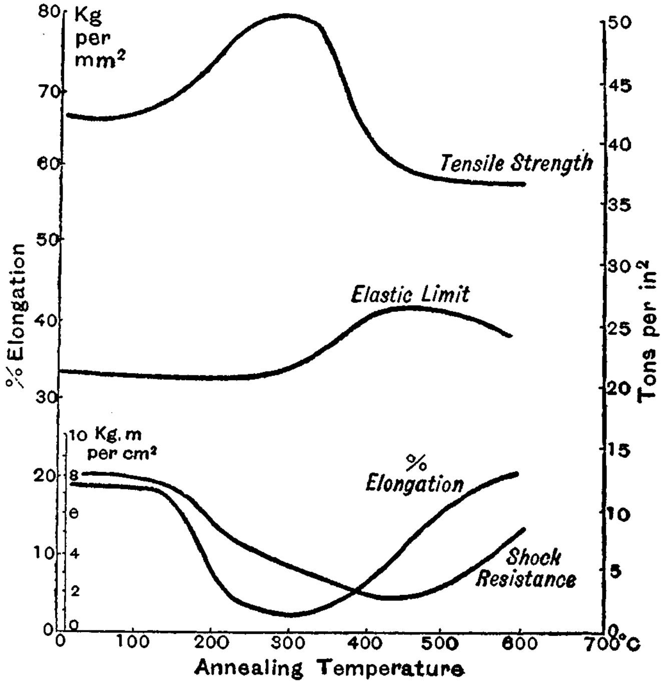


FIG. 70.—Variation in Mechanical Properties (Tensile and Impact) with Temperature of Reanneal after Quenching from 700°. Forged Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

(1) *Reanneal after Quenching from* 700°.

The results are summarised in Fig. 70.

The reanneal which produces the best Tensile Strength and Elastic Limit is one at 300°, giving the following values :—

Tensile Strength =80 kg. per sq. mm. (50·8 tons per sq. in.)
Elastic Limit =55 kg. per sq. mm. (34·92 tons per sq. in.)
% Elongation = 2
Shock Resistance = 3 kg. m. per sq. cm.

The reanneal which produces the best Elongation and Shock Resistance is one at 600°, when the values are—

Tensile Strength =58 kg. per sq. mm. (36·83 tons per sq. in.)
Elastic Limit =36 kg. per sq. mm. (22·86 tons per sq. in.)
% Elongation =20
Shock Resistance = 5 kg. m. per sq. cm.

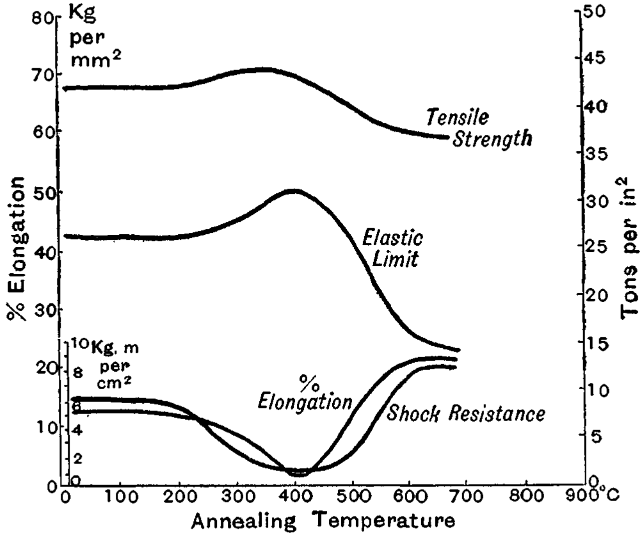


FIG. 71.—Variation in Mechanical Properties (Tensile and Impact) with Temperature of Reanneal after Quenching from 800°. Forged Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

It must be noted that the first reanneal corresponds with unsuitable Elongation and too great brittleness, and the second reanneal has no advantage over simply quenching from 700°, when—

Tensile Strength =66 kg. per sq. mm. (41·92 tons per sq. in.)
Elastic Limit =34 kg. per sq. mm. (21·59 tons per sq. in.)
% Elongation =18
Shock Resistance= 7 kg.m. per sq. cm.

In conclusion, reannealing after quenching from 700° gives the alloy no valuable properties.

(2) *Reanneal after Quenching from* 800°.

The results are summarised in Fig. 71.

The reanneal which gives the best Tensile Strength and Elastic Limit is one at about 400°, when the values are :—

Tensile Strength =70 kg. per sq. mm. (44·45 tons per sq. in.)
Elastic Limit =50 kg. per sq. mm. (31·75 tons per sq. in.)
% Elongation = 2
Shock Resistance = 1 kg. m. per sq. cm.

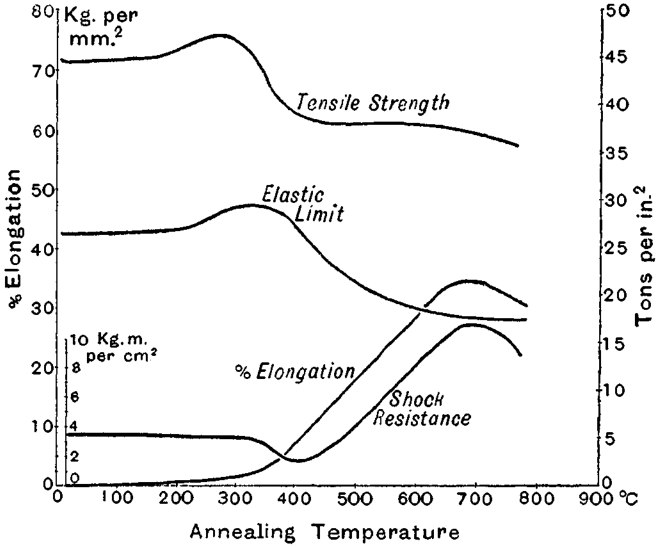


FIG. 72.—Variation in Mechanical Properties (Tensile and Impact) with Temperature of Reanneal after Quenching from 900°. Forged Aluminium Bronze, Type I (Cu 90 %, Al 10 %).

The reanneal which produces the best Elongation and Shock Resistance is one at about 600°, when the values are :—

Tensile Strength =60 kg. per sq. mm. (38·10 tons per sq. in.)
Elastic Limit =26 kg. per sq. mm. (16·51 tons per sq. in.)
% Elongation =22
Shock Resistance = 8 kg. m. per sq. cm.

Similar remarks apply to these two reanneals as in the preceding case.

(3) *Reanneal after Quenching from* 900°.

The results are summarised in Fig. 72.

The reanneal which gives the best Tensile Strength and Elastic Limit is one at about 300°, when the values are :—

Tensile Strength =75 kg. per sq. mm. (47·62 tons per sq. in.)
Elastic Limit =48 kg. per sq. mm. (30·48 tons per sq. in.)
% Elongation = 0·5
Shock Resistance = 3 kg. m. per sq. cm.

The reanneal which gives the best Elongation and Shock Resistance is one at about 600°, when the values are :—

Tensile Strength =58 kg. per sq. mm. (36·83 tons per sq. in.)
Elastic Limit =28 kg. per sq. mm. (17·78 tons per sq. in.)
% Elongation =34
Shock Resistance =12 kg. m. per sq. cm.

The first reanneal is of no value on account of the great brittleness that it causes. On the contrary, the second reanneal is of the greatest importance since it produces in aluminium bronze most remarkable properties, namely :—

(*a*) Elongations comparable with, or even superior to, those of the softest steels or of high nickel steels (more than 30 % nickel).
(*b*) A sufficiently large Shock Resistance.
(*c*) Tensile Strengths comparable with those of tempered steels.

CONCLUSION.

The following is the optimum thermal treatment for cupro-aluminium (Type I) (90 % copper, 10 % aluminium) :—

Quenching from 900°.
Reannealing at 675°–700°.

(*f*) HARDNESS AT HIGH TEMPERATURES.

Hardness tests at high temperatures were carried out on cylinders, 2 cm. in diameter, and 2 cm. high, as in the case of the light alloys of great strength.

A ball, 10 mm. in diameter, was used under a load of 500 kg., and the tests were made at every fifty degrees from the normal temperature up to 800°.

The hardness at high temperatures of cupro-aluminium, Type I, was investigated under three conditions :—

(1) Alloy as forged (worked).
(2) Alloy as cast.
(3) Alloy quenched from 900° and reannealed at 700°.

The results of the tests are summarised in Fig. 72*b*, and may be stated as follows :—

Normal Temperature.

Hardness of worked alloy under 500 kg. =150–160
Hardness of cast alloy under 500 kg. =100–110
Hardness of quenched and reannealed alloy under 500 kg.=110–120

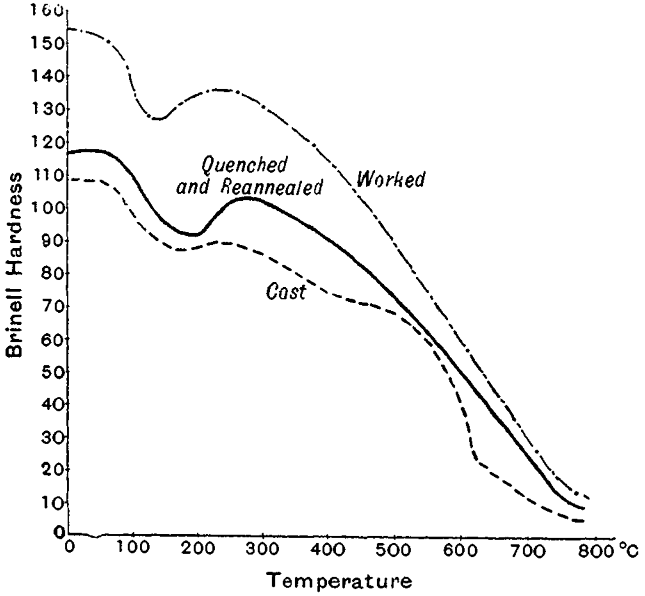


FIG. 72*b*.—High-temperature Hardness Tests (500 Kg.) on Aluminium Bronze, Type I :—

——————— quenched from 900°, reannealed at 700°.
—— · —— · —— after work (forging—pressing).
— — — — — — — as cast.

Effect of Temperature.

The alloy, Type I, possesses in all three states a minimum hardness over the range of temperature 100–200°.

The worked alloy retains a greater hardness at all temperatures.

The cast alloy, although less hard than the other two, has, still, at high temperatures, an appreciable value. (Compare results with those of the casting alloys.)

The heat-treated alloy possesses at all temperatures a hardness lying between the two preceding.

II. Type II

Cupro-Aluminiums containing 89 % Copper, 10 % Aluminium, 1 % Manganese

(*a*) Chemical Analysis.

Copper	89
Aluminium	9·50
Manganese	0·95
Iron	0·25
Nickel	nil
Lead	nil
Tin	nil
Difference	0·30
	100·00

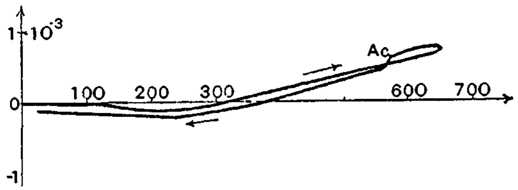


Fig. 73.—Aluminium Bronze, Type II.

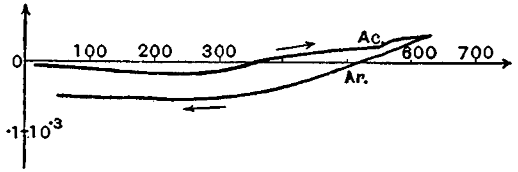


Fig. 74.—Aluminium Bronze, Type II.

(*b*) Investigation of Critical Points.

Cupro-aluminium, Type II, undergoes a single transformation on heating, as also on cooling (see Figs. 73 and 74).

(*c*) Variation in the Mechanical Properties, Tensile and Impact, with the Annealing Temperature, of the Forged Alloy, Type II.

The results of the tests are summarised in Fig. 75, which shows that a single anneal is of no value, the alloy in the forged state possessing the following properties:—

Tensile Strength = 55 kg. per sq. mm. (34·92 tons per sq. in.)
Elastic Limit = 24 kg. per sq. mm. (15·24 tons per sq. in.)
% Elongation = 3·5
Shock Resistance = 4·5 kg. m. per sq. cm.

ǀ VARIATION IN THE MECHANICAL PROPERTIES, TENSILE AND IMPACT, WITH THE QUENCHING TEMPERATURE, FORGED ALLOY, TYPE II.

The results of the tests are summarised in Fig. 76.

It is only after the transformation point has been passed, · between 500° and 600°, that the effect of the quenching comes visible.

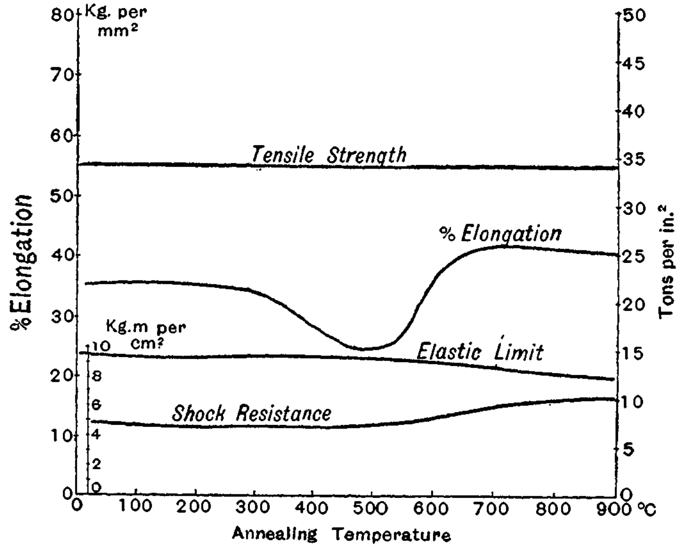


FIG. 75.—Variation in Mechanical Properties (Tensile and Impact) with Annealing Temperature. Forged Aluminium Bronze, Type II (Cu 89 %, Mn 1 %, Al 10 %).

The maximum properties after quenching, not followed by reanneal, are produced by quenching from 700°, when these lues are as follows :—

Tensile Strength =55 kg. per sq. mm. (34·92 tons per sq. in.)
Elastic Limit =24 kg. per sq. mm. (15·24 tons per sq. in.)
% Elongation =35
Shock Resistance =12 kg. m. per sq. cm.

This treatment without reanneal is, therefore, of value only regards Shock Resistance for alloys of Type II, the Shock sistance being 12 kg. m. per sq. cm. instead of 4·5, as in the ged state, but the other properties remain approximately e same.

(*e*) VARIATION IN THE MECHANICAL PROPERTIES, TENSILE AND IMPACT, WITH TEMPERATURE OF REANNEAL, SUBSEQUENT TO QUENCHING THE FORGED ALLOY, TYPE II.

The following quenching temperatures were studied: 800° and 900°.

The reanneals were carried out under the same conditions as in the case of Type I.

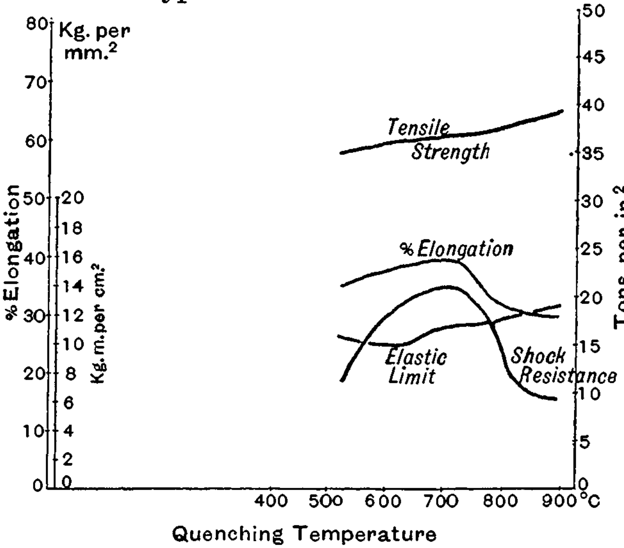


FIG. 76.—Variation in Mechanical Properties (Tensile and Impact) with Quenching Temperature. Forged Aluminium Bronze, Type II (Cu 89 %, Mn 1 %, Al 10 %).

(1) *Reanneal after Quenching from* 800°.

The results are summarised in Fig. 77.

The anneal which produces the best Tensile Strength and Elastic Limit is one at about 400°, when the values are :—

Tensile Strength =70 kg. per sq. mm. (44·45 tons per sq. in.)
Elastic Limit =28 kg. per sq. mm. (17·78 tons per sq. in.)
% Elongation =14
Shock Resistance= 3 kg. m. per sq. cm.

On the other hand, the anneal producing the best Elongation and Shock Resistance is one at 750°, when the values are :—

Tensile Strength =54 kg. per sq. mm. (34·29 tons per sq. in.)
Elastic Limit =22 kg. per sq. mm. (13·97 tons per sq. in.)
% Elongation =38
Shock Resistance=14 kg. m. per sq. cm.

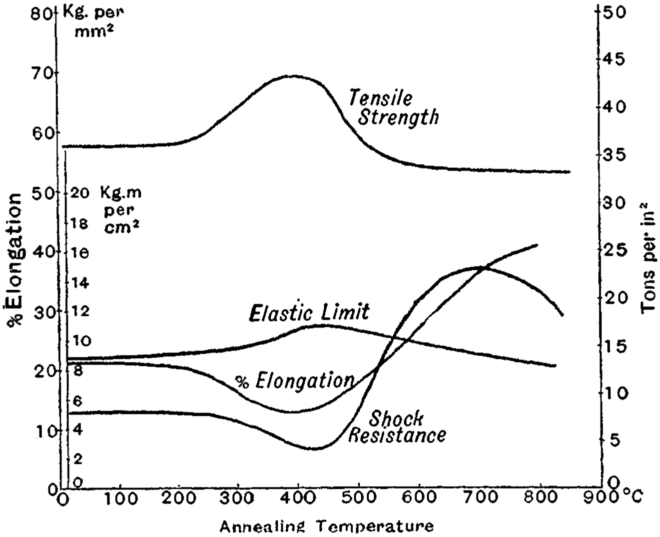


FIG. 77.—Variation in Mechanical Properties (Tensile and Impact) with Temperature of Reanneal after Quenching from 800°. Forged Aluminium Bronze, Type II (Cu 89 %, Mn 1 %, Al 10 %).

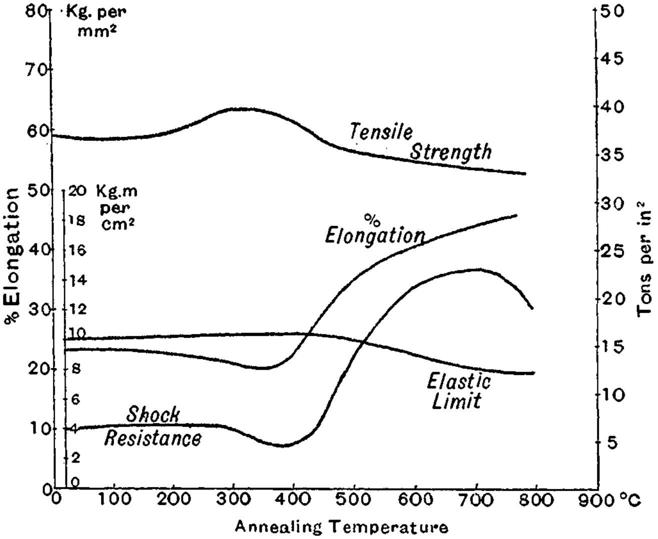


FIG. 78.—Variation in Mechanical Properties (Tensile and Impact) with Temperature of Reanneal after Quenching from 900°. Forged Aluminium Bronze, Type II (Cu 89 %, Mn 1 %, Al 10 %).

(2) *Reanneal after Quenching from* 900°.

The results are summarised in Fig. 78.

The best Tensile Strength and Elastic Limit are produced by an anneal at about 350°, which does not cause any important changes in the alloy.

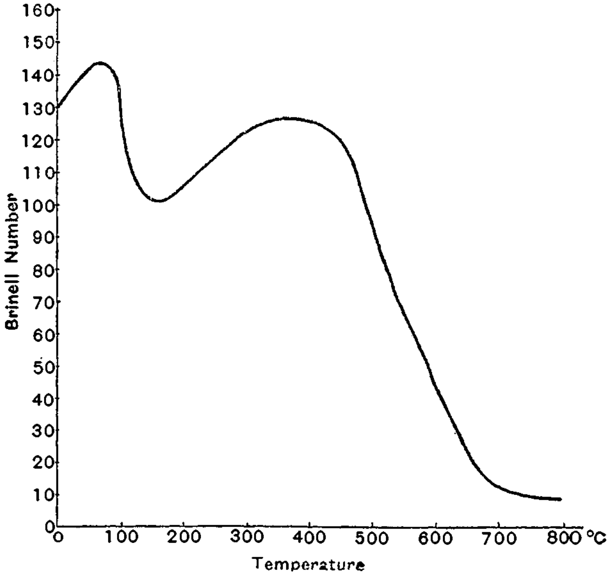


FIG. 78*b*.—High-temperature Hardness Tests (500 Kg.) on Aluminium Bronze, Type II, Quenched from 900°, Reannealed at 600°.

The best Elongation and Shock Resistance are produced by an anneal at about 750°, when the values are :—

Tensile Strength =54 kg. per sq. mm. (34·29 tons per sq. in.)
Elastic Limit =20 kg. per sq. mm. (12·7 tons per sq. in.)
% Elongation =45
Shock Resistance=14 kg. m. per sq. cm.

This cupro-aluminium, containing 1 % manganese, acquires, as a result of this treatment, very remarkable properties.

The Tensile Strength and Elastic Limit, approaching those of the tempered steels, are surpassed in importance by the great Elongation and unusual Shock Resistance.

CONCLUSION.

The optimum thermal treatment for cupro-aluminium containing 1 % of manganese, i.e. Type II, is as follows : quenching from 900°, followed by reannealing at 750°.

(*f*) Hardness at High Temperatures.

The hardness tests at high temperatures were carried out under the same conditions as for Type I, and the results are shown in Fig. 78*b*.

They were carried out only on the heat-treated alloy (quenched from 900° and reannealed at 600°).

They reveal a greater hardness than that of Type I for all temperatures between 0° and 500°, but a slightly lower hardness for temperatures above 500°.

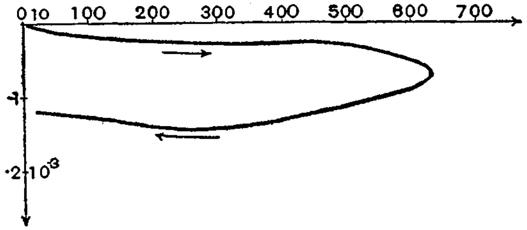


Fig. 79.—Aluminium Bronze, Type III (Dilatometer).

III. Type III

81 % Copper, 11 % Aluminium, 4 % Nickel, 4 % Iron

(*a*) Chemical Analysis.

Copper	80·95
Aluminium	10·60
Manganese	0·45
Iron	4·40
Nickel	3·55
Lead	nil
Tin	nil
Difference	0·05
	100·00

(*b*) Investigation of the Critical Points.

Neither the expansion curve nor the curve of temperature plotted against time indicates the slightest transformation (see Figs. 79 and 80).

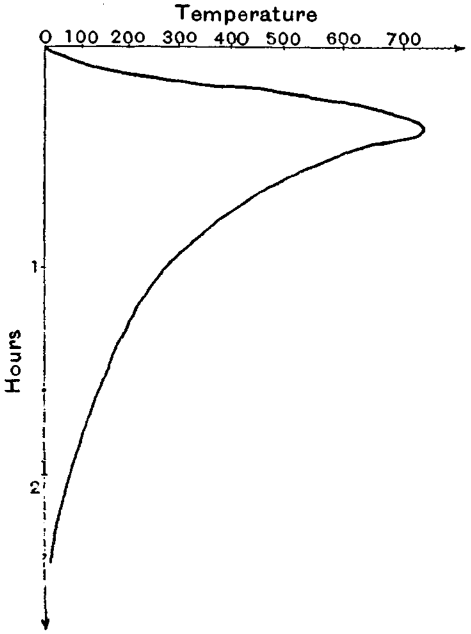


FIG. 80.—Aluminium Bronze, Type III, Temperature Time Curve.

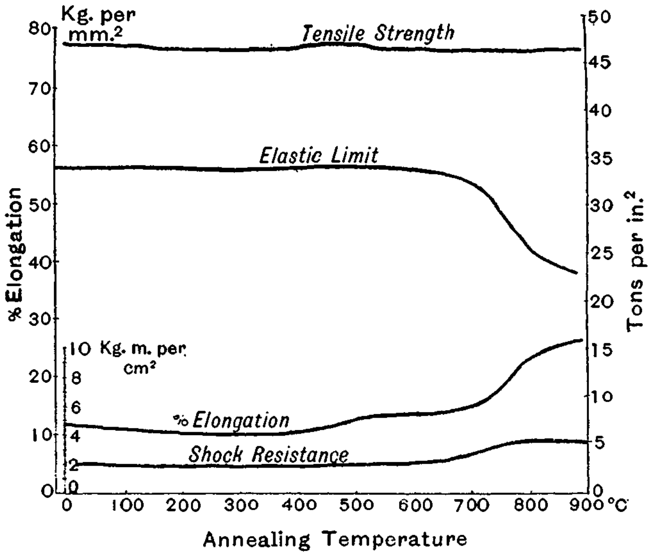


FIG. 81.—Variation in Mechanical Properties (Tensile and Impact) with Annealing Temperature. Forged Aluminium Bronze, Type III (Cu 81 %, Ni 4 %, Fe 4 %, Al 11 %).

(c) Variation in the Mechanical Properties, Tensile and Impact, with the Annealing Temperature, for the Forged Alloy, Type III.

The results of the tests are summarised in Fig. 81, which shows that this cupro-aluminium in the forged state possesses the following properties :—

Tensile Strength = 76 kg. per sq. mm. (48·26 tons per sq. in.)
Elastic Limit = 56 kg. per sq. mm. (35·56 tons per sq. in.)
% Elongation = 12
Shock Resistance = 2 kg. m. per sq. cm.

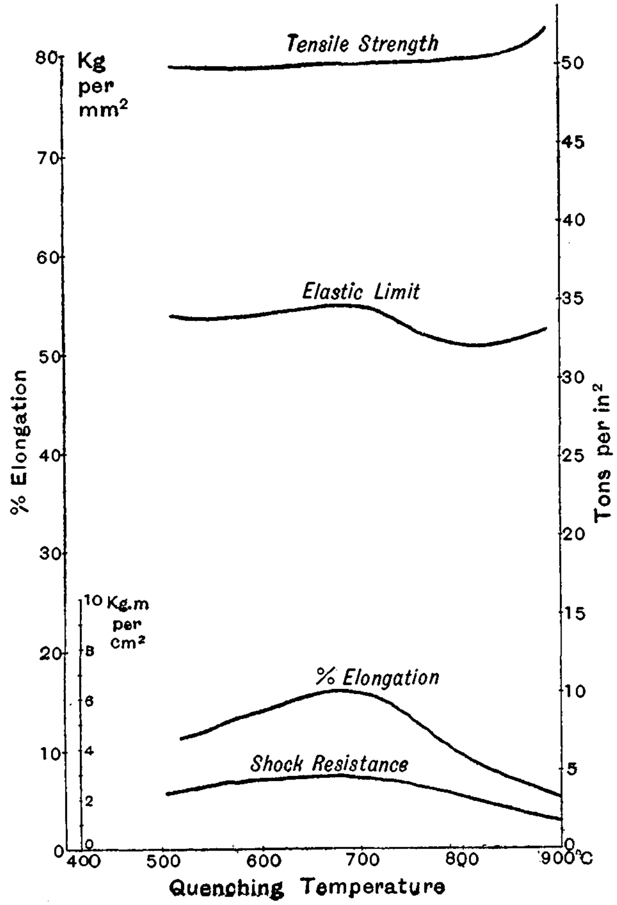


Fig. 82.—Variation in Mechanical Properties (Tensile and Impact) with Quenching Temperature. Forged Aluminium Bronze, Type III (Cu 81 %, Ni 4 %, Fe 4 %, Al 11 %).

Annealing seems to have no effect up to 400–500°. Above 500°, annealing has the effect of diminishing the Elastic Limit and of improving the Elongation and Shock Resistance, whilst the Tensile Strength remains unchanged.

Thus, after annealing at 900°, the alloy has the following properties :—

Tensile Strength =75 kg. per sq. mm. (47·62 tons per sq. in.)
Elastic Limit =36 kg. per sq. mm. (22·86 tons per sq. in.)
% Elongation =26
Shock Resistance= 4 kg. m. per sq. cm.

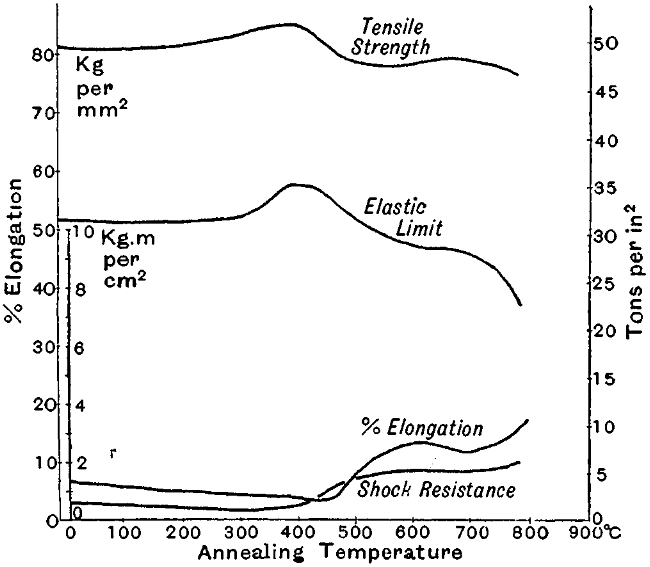


FIG. 83.—Variation in Mechanical Properties (Tensile and Impact) with Temperature of Reanneal after Quenching from 900°. Forged Aluminium Bronze, Type III (Cu 81 %, Ni 4 %, Fe 4 %, Al 11 %).

(*d*) VARIATION IN THE MECHANICAL PROPERTIES, TENSILE AND IMPACT, WITH THE QUENCHING TEMPERATURE FOR THE FORGED ALLOY, TYPE III.

The results of the tests are shown in Fig. 82, which shows that the change in the properties of the alloy after quenching is only insignificant.

(*e*) Variation in the Mechanical Properties, Tensile and Impact, with the Temperature of Reanneal, subsequent to Quenching the Forged Alloy, Type III.

The results of reannealing after quenching from 900° are shown in Fig. 83, which shows that the mechanical properties undergo no appreciable improvement after quenching from 900° and reannealing.

Conclusion.

The following method of working seems to be advisable: annealing at 900°, followed by cooling in air.

(*f*) Hardness at High Temperatures.

The results are summarised in Fig. 83*b*.

The tests were carried out on metal annealed at 900°, and show, for all temperatures, a hardness greater than that of the alloys of Types I and II.

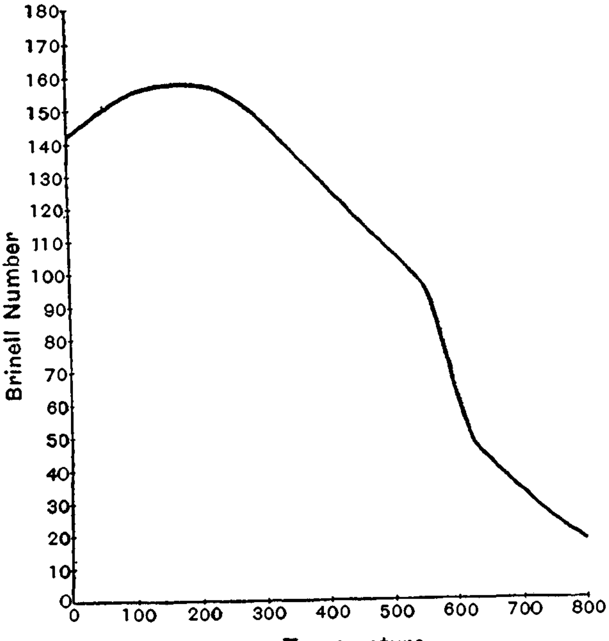


Fig. 83*b*.—High-temperature Hardness Tests (500 Kg.) on Aluminium Bronze, Type III, Annealed at 900°.

CHAPTER III

MICROGRAPHY

As we have seen, the alloys studied contain from 88 % to 92 % of copper, and in that range consist of the solid solution α plus the eutectoid $(\alpha+\gamma)$. At 88 % of copper, the alloy consists of almost pure eutectoid, below that value the γ constituent makes its appearance. We have, therefore, only to consider the hypoeutectoid alloys, and to study the solution α and the eutectoid $(\alpha+\gamma)$.

Experimental Details.

Shock test pieces, which had received varying treatment, were used for micrographic examination.

Robin's reagent was used for etching. This consists of :—

Ferric chloride . . .	5 %
Water	5 %
Hydrochloric acid . .	30 %
Isoamyl alcohol . .	30 %
Ethyl alcohol . . .	30 %

The following is the most general and complete scheme of investigation for a typical alloy :—

Micrographic examination of sections of

(*a*) Metal annealed after forging or casting.
(*b*) Metal quenched from different temperatures.
(*c*) Metal quenched and reannealed at different temperatures.
(*d*) Cast or worked metal.

I. Cupro-Aluminium, Type I

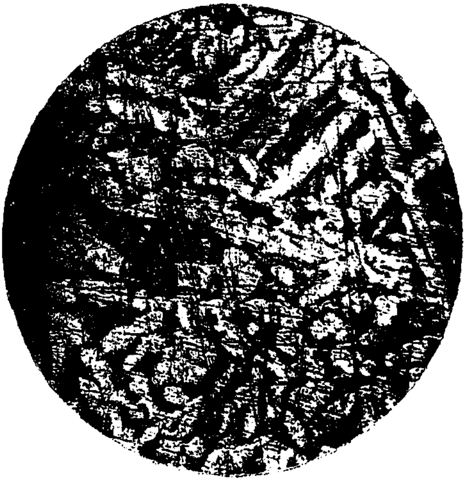
(*a*) Micrographic Examination of Sections of Metal Forged and subsequently Annealed at different Temperatures.

Plates I and II give the microphotographs of these sections. We will comment upon them in turn.

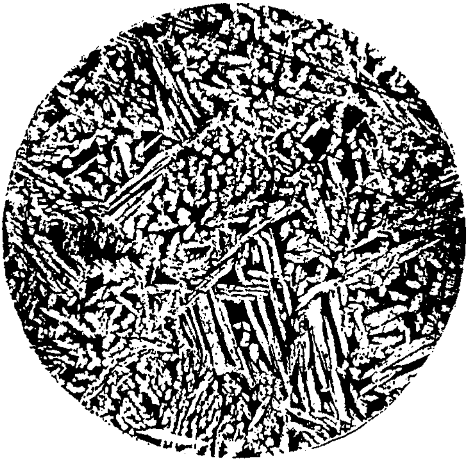
PLATE I.

TYPE I. FORGED AND ANNEALED.

PHOTOGRAPH 1.
CUPRO-ALUMINIUM. AS FORGED.
×60.



PHOTOGRAPH 2.
CUPRO-ALUMINIUM. AS FORGED.
×225.



PHOTOGRAPH 3.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY ANNEALED AT 300°.
×60.

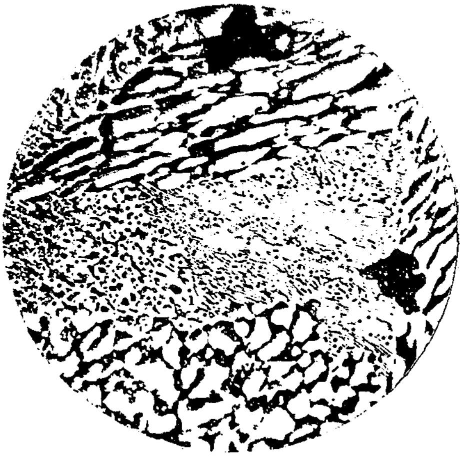
PHOTOGRAPH 4.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY ANNEALED AT 300°.
×225.

To face page 143

TYPE I. EUTECTIC STRUCTURE.

PHOTOGRAPH A.
EUTECTIC STRUCTURE. ETCHED WITH ALCOHOLIC FERRIC CHLORIDE.
× 500.
(Portevin.)

PHOTOGRAPH B.
EUTECTIC STRUCTURE. ETCHED WITH ALCOHOLIC FERRIC CHLORIDE.
× 870.
(Portevin.)



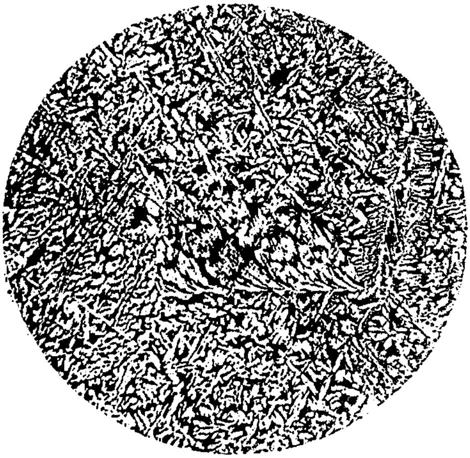
PHOTOGRAPH C.
SHOWING TWO EUTECTIC FORMATIONS— CELLULAR AND LAMELLAR.
× 500.
ETCHED WITH ALCOHOLIC FERRIC CHLORIDE.
(Portevin.)

PHOTOGRAPH D.
HYPEREUTECTOID ALLOY.
EUTECTIC + γ.
× 200.
ETCHED WITH ALCOHOLIC FERRIC CHLORIDE.
(Portevin.)

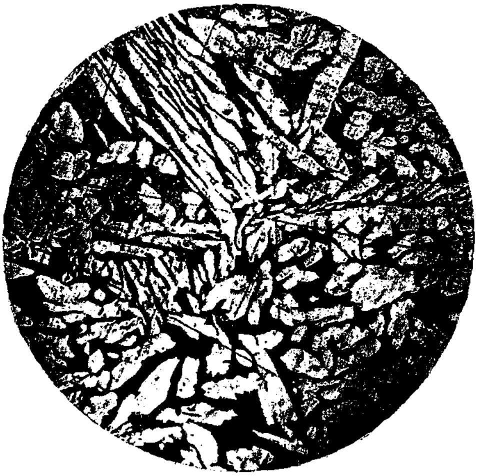
To face page 143

PLATE II.

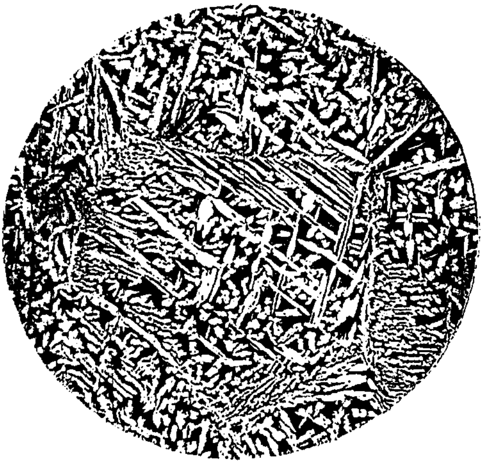
TYPE I. FORGED AND SUBSEQUENTLY ANNEALED.



PHOTOGRAPH 5.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY ANNEALED AT 700°.
×60.



PHOTOGRAPH 6.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY ANNEALED AT 700°.
×225.



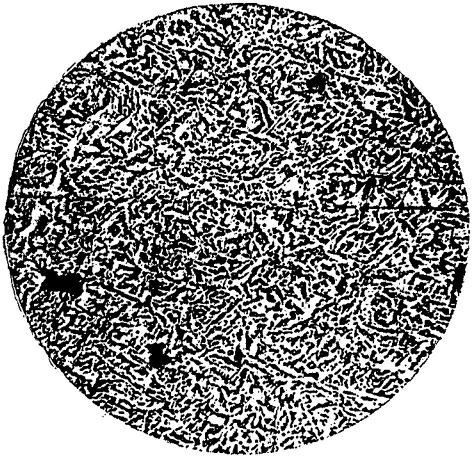
PHOTOGRAPH 7.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY ANNEALED AT 900°.
×60.

PHOTOGRAPH 8.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY ANNEALED AT 900°.
×225.

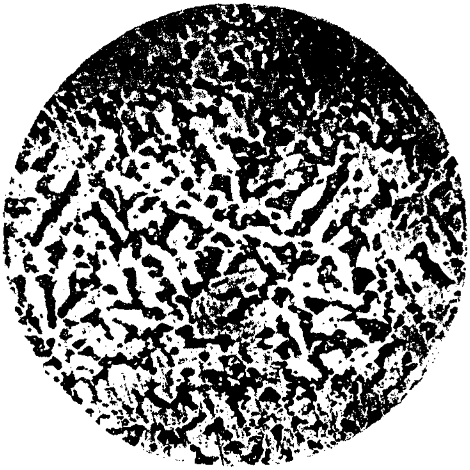
To face page 143.

PLATE III.

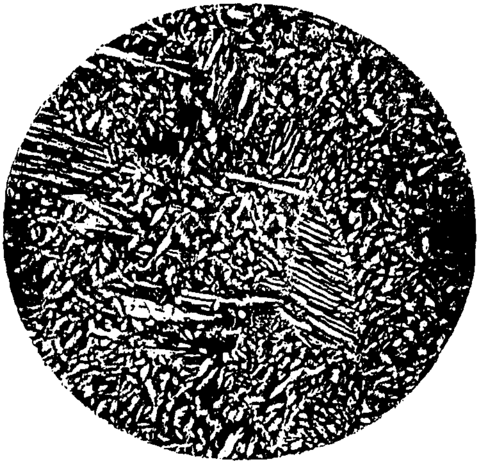
TYPE I. FORGED AND SUBSEQUENTLY QUENCHED.



PHOTOGRAPH 9.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 500°.
× 60.



PHOTOGRAPH 10
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 500°.
× 225.



PHOTOGRAPH 11.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 600°.
× 60.

PHOTOGRAPH 12.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 600°.
× 225.

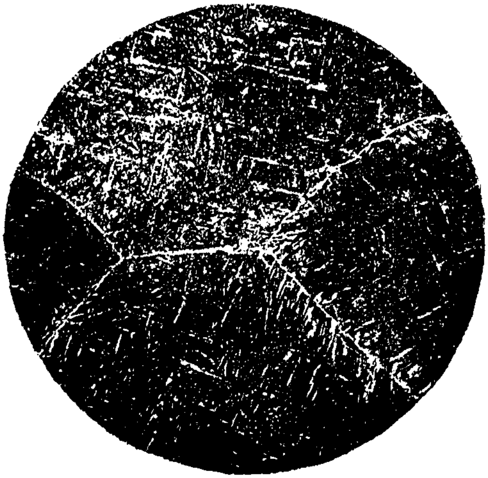
To face page 143.

PLATE IV.

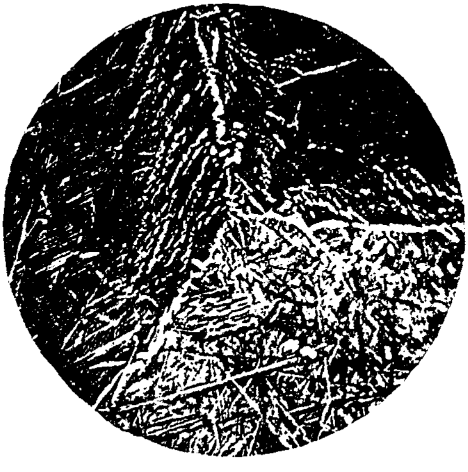
TYPE I. FORGED AND SUBSEQUENTLY QUENCHED.

PHOTOGRAPH 13.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 700°.
×60.
(Breuil.)

PHOTOGRAPH 14.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 700°.
×225.
(Breuil.)



PHOTOGRAPH 15.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 800°.
×60.
(Breuil.)



PHOTOGRAPH 16.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 800°.
×225.
(Breuil.)

To face page 143

PLATE V.

TYPE I. FORGED AND SUBSEQUENTLY QUENCHED.

PHOTOGRAPH 17.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 900°.
×60.
(Breuil.)

PHOTOGRAPH 18.
CUPRO-ALUMINIUM. FORGED AND SUBSEQUENTLY QUENCHED FROM 900°.
×225.
(Breuil.)

(i) *Forged Alloy* (not subsequently annealed).

See Photographs 1 and 2 of Plate I.

We note the two constituents previously mentioned—the α constituent and the $(\alpha+\gamma)$ eutectoid, which we will call E. The α constituent appears as white dendrites, while the eutectoid appears black.

According to Portevin,* the constitution of the eutectoid is as follows :—

"The β constituent † of the aluminium bronzes can exhibit two formations, firstly, a cellular or honeycombed network; and, secondly, a considerably finer, lamellar, structure, analogous to the pearlite in annealed steels.

These two formations can coexist in contiguous portions of the same alloy, the reticular form being favoured in the portions adjacent to the proeutectoid constituent α.

The lamellar form of eutectic is only capable of resolution under high magnifications in slowly cooled alloys, while, under the same conditions of cooling, the reticular form is visible under low magnifications."

See Portevin's microphotographs, Plate IB.

(ii) *Effect of Annealing after Forging.*

See Photographs 3–8 inclusive, Plates I and II.

Whatever the temperature of anneal after forging, the constituent α and the eutectoid E are seen to be present. Annealing leads to a certain amount of separation of the dendrites of the α constituent; the needles arrange themselves in parallel lines, and the intersections of the various groups give rise to polyhedric outlines, forming, as it were, the crystal boundaries. These outlines increase in size as the temperature rises—a high temperature anneal practically gives rise to exaggerated grain size. This, however, does not involve a lowering of the percentage Elongation or of the Shock Resistance, as occurs in steel and certain alloys.

Breuil explains this phenomenon on the assumption that crystals possessing a given orientation are united to those in an adjacent zone by means of connecting filaments, without there being any abrupt break, as in certain other metals.

* Portevin, "Internationale Zeitschrift für Metallographie," X, 948, 1913.

† The author refers to the $(\alpha+\gamma)$ eutectoid as β. We call this E. The term "β" should be retained, as curry's diagram shows, for the constituent analogous to the austenite in steels.

(b) MICROGRAPHIC EXAMINATION OF SECTIONS QUENCHED AND NOT SUBSEQUENTLY ANNEALED.

The diagrams relating to critical points revealed the fact that all these points only make their appearance if the temperature exceeds 500°.

The highest point, Ac_3, plays an essential part, and must be passed, on heating, if structural modifications are to be expected on cooling.

Actually, Ac_3 appears at about 570°, and Ar_1, on cooling, occurs at 520°. It is, therefore, only above 600° that the effect of quenching becomes appreciable.

Generally speaking, quenched alloys exhibit a martensitic, acicular structure, possessing a triangular arrangement. The structure varies with the quenching conditions, thus showing a very great similarity to the martensite of steels.

The α constituent seems gradually to disappear as the quenching temperature rises. It seems to be reabsorbed or to dissolve in the eutectoid E in the form of fine white needles. This solution we shall call M, in order not to employ the letter γ, often used, but which, in Curry's diagram, has a different significance.

Looking at the microphotographs 9–18 inclusive, Plates III, IV, and V,* we observe the progressive disappearance of the separate constituent. It is present after quenching from 500°, slightly lessened in amount after quenching from 600°, extremely diminished in amount after quenching from 700°, and has almost completely disappeared after quenching from 800°.

For quenching to be complete, therefore, the temperature must rise considerably above the critical point, which occurs at 570°, and at which the transformation commences.

We may presume that an increase in the times of anneal would have the same effect as a rise in temperature, i.e. that a very prolonged anneal at 750° would give the same results as an anneal of much shorter duration at 850°.

However that may be, for normal and industrial annealing times, it is necessary that the temperature should exceed 800°, for the solution M to extend throughout the whole mass of metal. It can only be decided whether 800° or 900° should be employed after studying the effects of reannealing.

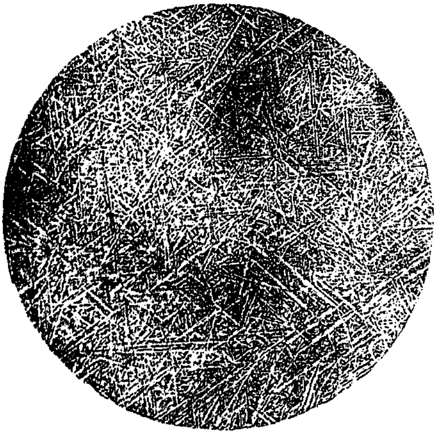
* Photographs 13–18, inclusive, are taken from a research by Brouil on this particular alloy (known as mangalum, No. 100, Société des Bronzes forgeables, 31st May, 1918).

PLATE VI.

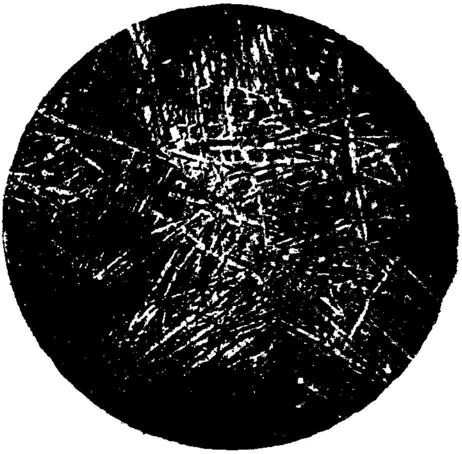
TYPE I. FORGED, QUENCHED, AND REANNEALED.

Photograph 19.
Cupro-aluminium. Forged, quenched from 900°, reannealed at 300°.
× 60.

Photograph 20.
Cupro-aluminium. Forged, quenched from 900°, reannealed at 300°.
× 225.



Photograph 21.
Cupro-aluminium. Forged, quenched from 900°, reannealed at 600°.
× 60.

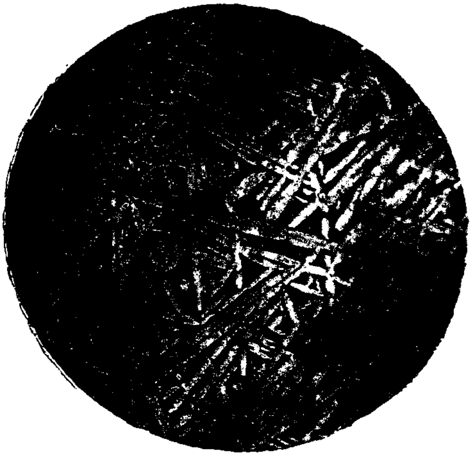


Photograph 22.
Cupro-aluminium. Forged, quenched from 900°, reannealed at 600°.
× 225.

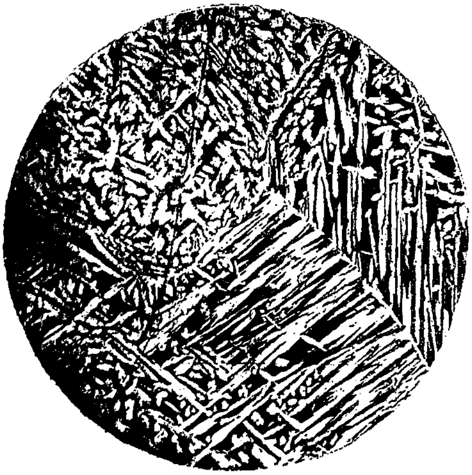
PLATE VII.

TYPE I. FORGED, QUENCHED, AND REANNEALED.

PHOTOGRAPH 23.
CUPRO-ALUMINIUM. FORGED, QUENCHED FROM 900°, REANNEALED AT 700°.
×60.



PHOTOGRAPH 24.
CUPRO-ALUMINIUM. FORGED, QUENCHED FROM 900°, REANNEALED AT 700°.
×225.

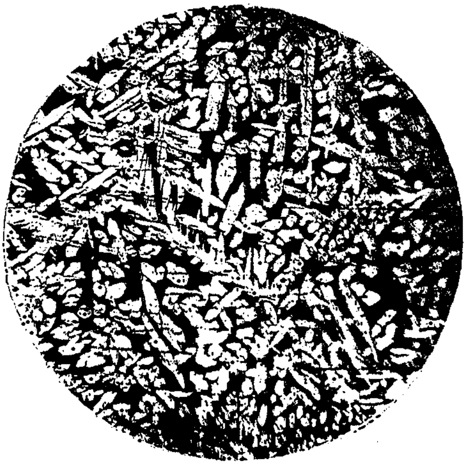


PHOTOGRAPH 25.
CUPRO-ALUMINIUM. FORGED, QUENCHED FROM 900°, REANNEALED AT 800°.
×60.

PHOTOGRAPH 26.
CUPRO-ALUMINIUM. FORGED, QUENCHED FROM 900°, REANNEALED AT 800°.
×225.

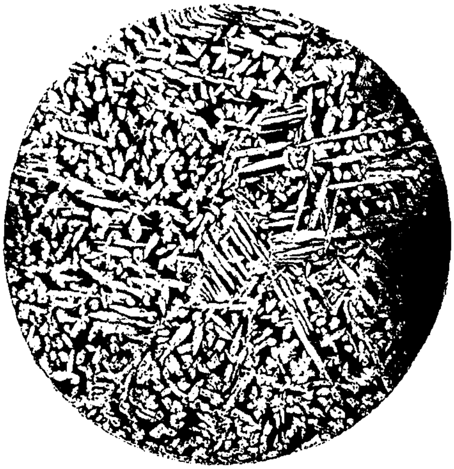
PLATE VIII.

TYPE I. CAST AND ANNEALED.



PHOTOGRAPH 27.
CUPRO-ALUMINIUM. AS CAST.
×60.

PHOTOGRAPH 28.
CUPRO-ALUMINIUM. AS CAST.
×225.

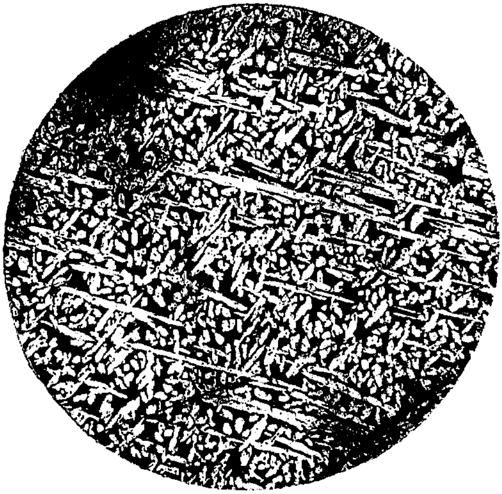


PHOTOGRAPH 29.
CUPRO-ALUMINIUM. CAST AND ANNEALED AT 800°.
×60.

PHOTOGRAPH 30.
CUPRO-ALUMINIUM. CAST AND ANNEALED AT 800°.
×225.

PLATE IX.

TYPE I. CAST AND ANNEALED.



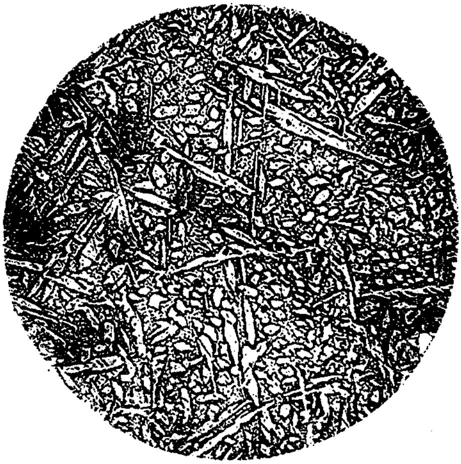
PHOTOGRAPH 31.
CUPRO-ALUMINIUM. CAST AND ANNEALED AT 900°.
×60.

PHOTOGRAPH 32.
CUPRO-ALUMINIUM. CAST AND ANNEALED AT 900°.
×225.

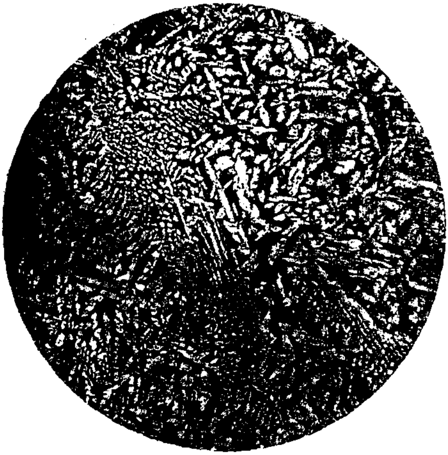
To face page 144.

PLATE X.

TYPE I. CAST AND QUENCHED.



PHOTOGRAPH 33.
CUPRO-ALUMINIUM. CAST AND QUENCHED FROM 500°.
×60.



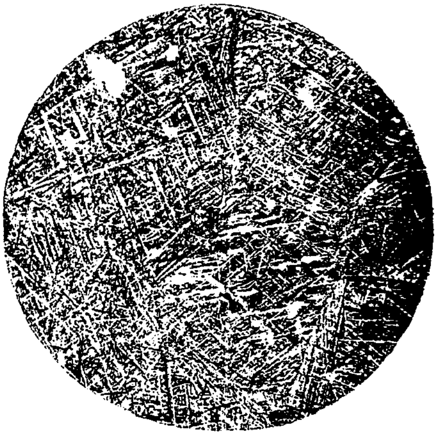
PHOTOGRAPH 34.
CUPRO-ALUMINIUM. CAST AND QUENCHED FROM 600°.
×60.

PHOTOGRAPH 35.
CUPRO-ALUMINIUM. CAST AND QUENCHED FROM 700°.
×60.

To face page 144.

PLATE X.—*continued.*

TYPE I. CAST AND QUENCHED.



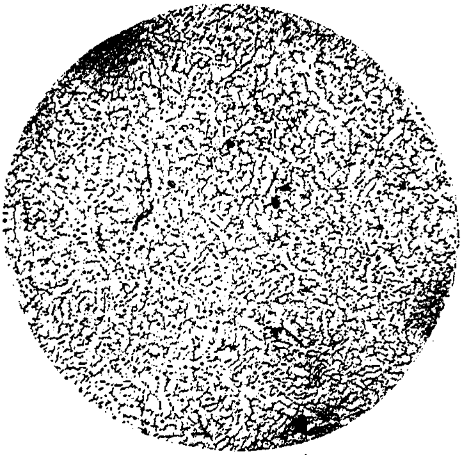
PHOTOGRAPH 36.
CUPRO-ALUMINIUM. CAST AND
QUENCHED FROM 800°.
× 60.

PHOTOGRAPH 37.
CUPRO-ALUMINIUM. CAST AND
QUENCHED FROM 900°.
× 60.

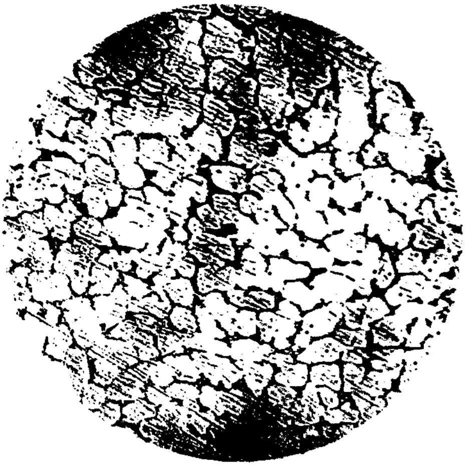
To face page 134.

PLATE XI.

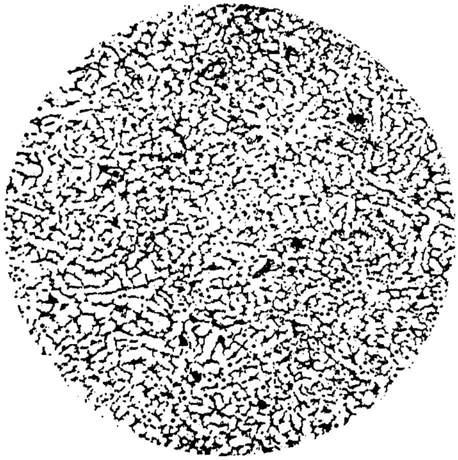
TYPE II. FORGED AND ANNEALED.



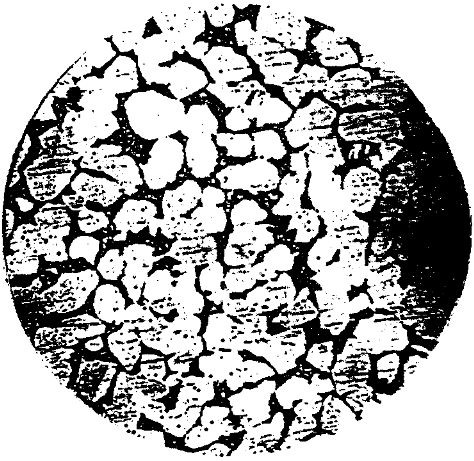
Photograph 38.
Cupro-aluminium. As forged.
× 60.



Photograph 39.
Cupro-aluminium. As forged.
× 225.



Photograph 40.
Cupro-aluminium. Forged and subsequently annealed at 800°.
× 60.

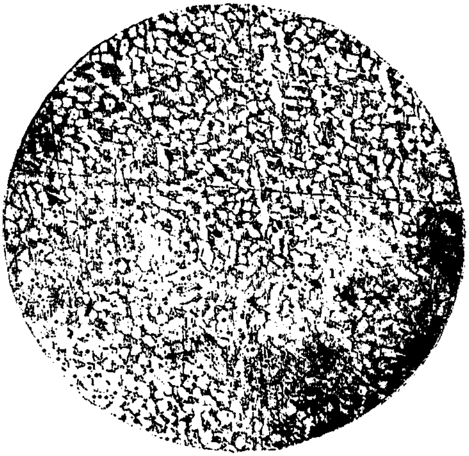


Photograph 41.
Cupro-aluminium. Forged and subsequently annealed at 800°.
× 225.

To face page 144

PLATE XII.

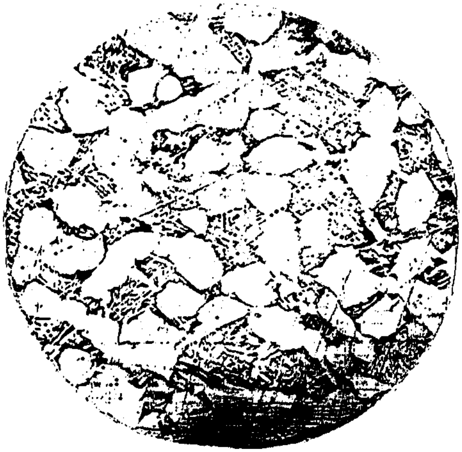
TYPE II. QUENCHED AND REANNEALED.



PHOTOGRAPH 42.

CUPRO-ALUMINIUM. QUENCHED FROM 900°, REANNEALED AT 600°.

× 60.



PHOTOGRAPH 43.

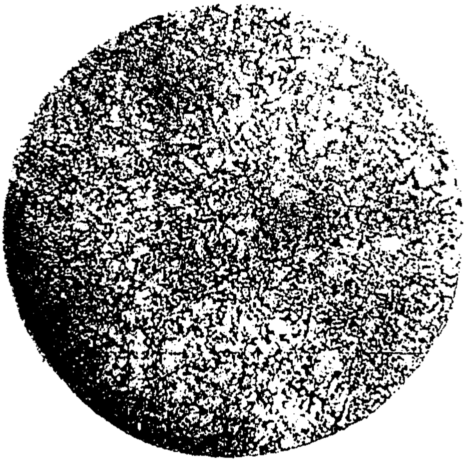
CUPRO-ALUMINIUM. QUENCHED FROM 900°, REANNEALED AT 600°.

× 225.

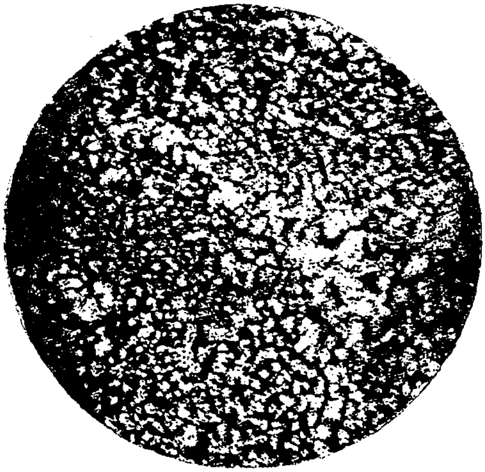
To face page 144

PLATE XIII.

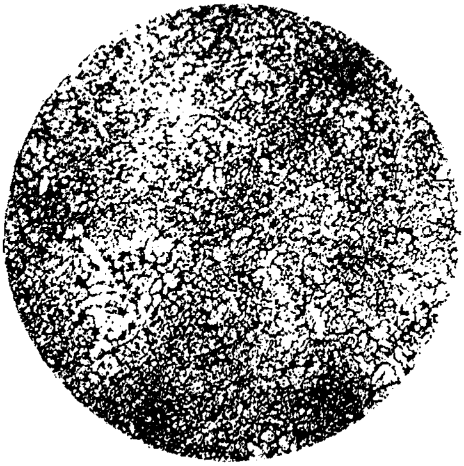
TYPE III. FORGED AND ANNEALED.



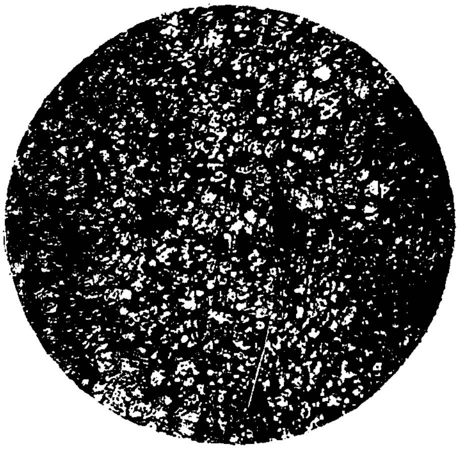
Photograph 44.
Cupro-aluminium. As forged.
× 60.



Photograph 45.
Cupro-aluminium. As forged.
× 225.



Photograph 46.
Cupro-aluminium. Forged and annealed at 600°.
× 60.

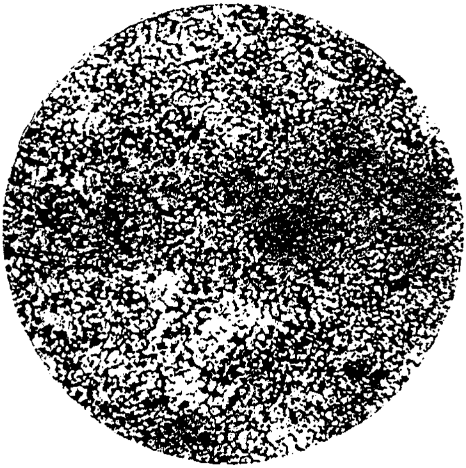


Photograph 47.
Cupro-aluminium. Forged and annealed at 600°.
× 225.

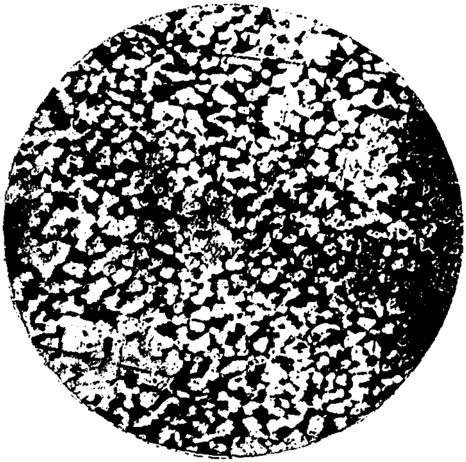
To face page 144.

PLATE XIV.

TYPE III. FORGED AND ANNEALED.



PHOTOGRAPH 48.
CUPRO-ALUMINIUM. FORGED AND ANNEALED AT 800°.
×60.

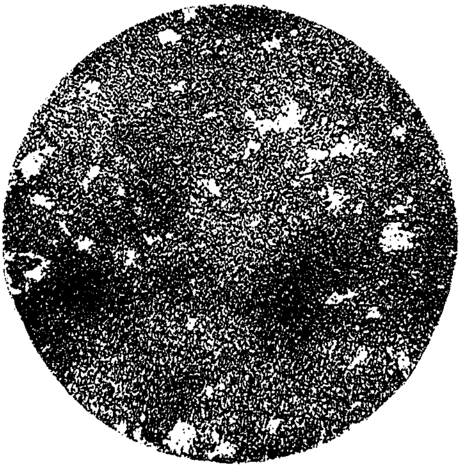


PHOTOGRAPH 49.
CUPRO-ALUMINIUM. FORGED AND ANNEALED AT 900°.
×225.

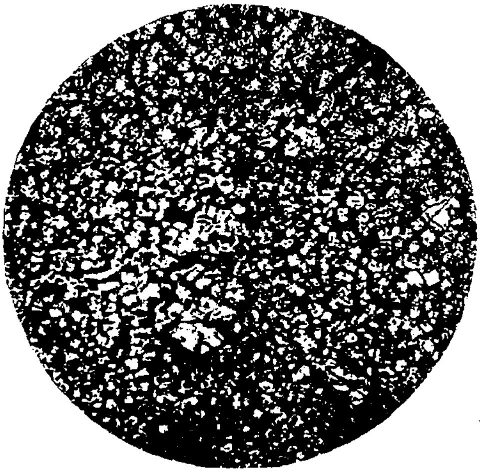
To face page 144.

PLATE XV.

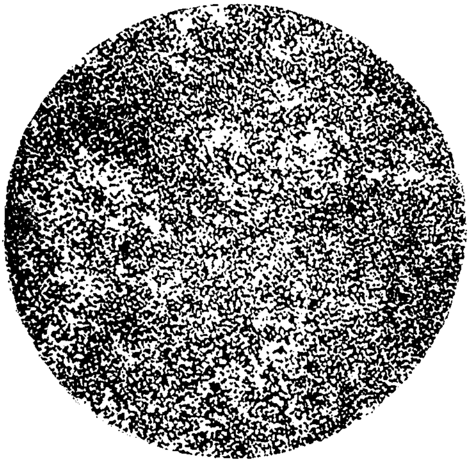
TYPE III. FORGED AND QUENCHED.



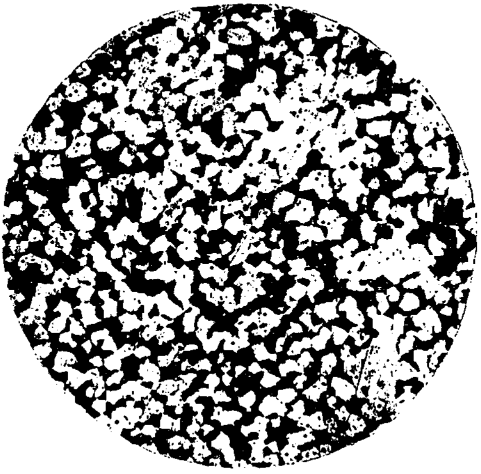
PHOTOGRAPH 50.
CUPRO-ALUMINIUM. QUENCHED FROM 500°.
× 60.



PHOTOGRAPH 51.
CUPRO-ALUMINIUM. QUENCHED FROM 500°.
× 225.



PHOTOGRAPH 52.
CUPRO-ALUMINIUM. QUENCHED FROM 800°.
× 60.

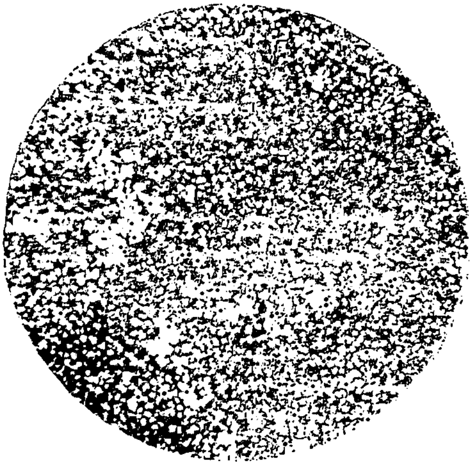


PHOTOGRAPH 53.
CUPRO-ALUMINIUM. QUENCHED FROM 800°.
× 225.

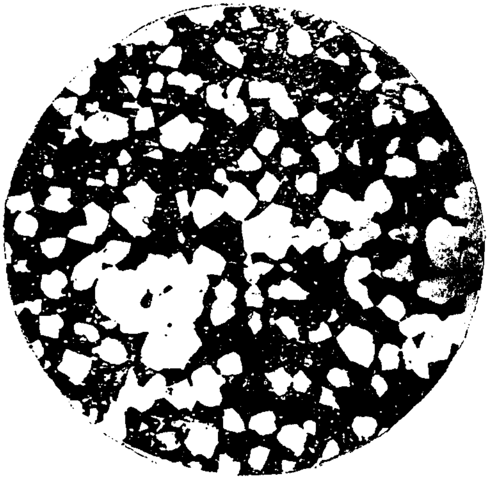
To face page 141.

PLATE XVI.

TYPE III. FORGED AND QUENCHED.



PHOTOGRAPH 54.
CUPRO-ALUMINIUM. QUENCHED FROM 900°.
×60.

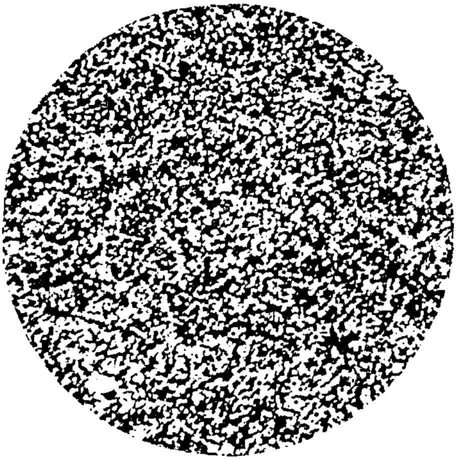


PHOTOGRAPH 55.
CUPRO-ALUMINIUM. QUENCHED FROM 900°.
×225.

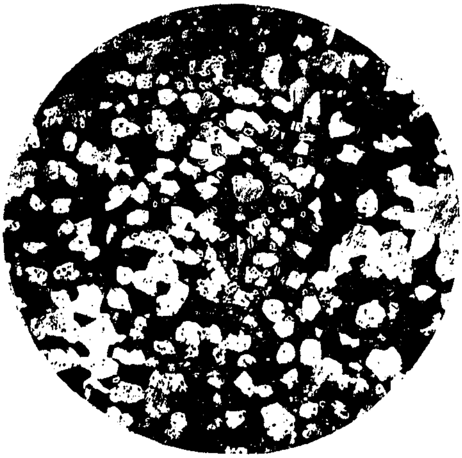
To face page 144.

PLATE XVII.

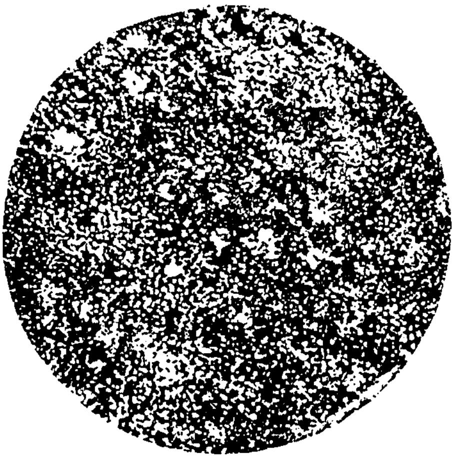
TYPE III. QUENCHED AND REANNEALED.



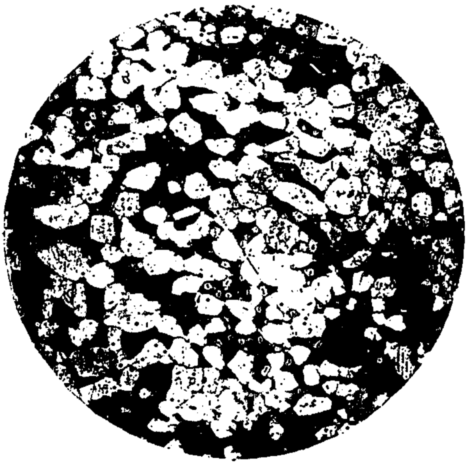
PHOTOGRAPH 56.
CUPRO-ALUMINIUM. QUENCHED FROM 900°, REANNEALED AT 500°.
× 60.



PHOTOGRAPH 57.
CUPRO-ALUMINIUM. QUENCHED FROM 900°, REANNEALED AT 500°.
× 225.



PHOTOGRAPH 58.
CUPRO-ALUMINIUM. QUENCHED FROM 900°, REANNEALED AT 600°.
× 60.



PHOTOGRAPH 59.
CUPRO-ALUMINIUM. QUENCHED FROM 900°, REANNEALED AT 600°
× 225.

To face page 144.

(*c*) Micrographic Examination of Sections Quenched and Reannealed.

Speaking generally, reannealing produces the reverse effects—the gradual reappearance of the α constituent. But the α constituent in a quenched and reannealed bronze presents a different appearance from that of the simply annealed metal. It is finer, more drawn out, and retains the acicular crystallite formation of the M constituent, as well as its arrangement. But the very fine needles of the M constituent are blunted and shortened in the new constituent α. This leads to an increase in the Shock Resistance, which, owing to the exclusive presence of the constituent M, quenching alone had considerably reduced.

(*d*) Micrographic Examination of Cast Specimens.

Microphotographs 27 and 28, Plate VIII, reveal the presence of the constituents α and E in cast specimens. Annealing these, as is easily seen, has not any considerable effect—a fact confirmed by mechanical tests (see Photographs 29–32 inclusive, Plates VIII–IX).

The microphotographs 33–37 inclusive, Plate X, show the effect of quenching cast aluminium bronze. After quenching from 800°, the almost complete disappearance of the α constituent and the presence of M throughout the mass may be observed.

Cast articles, as well as pressed, acquire by quenching the structure shown in the photographs.

Their mechanical properties are given in the appropriate chapter.

II. Cupro-Aluminium, Type II

The Photographs 38 and 39, Plate XI, refer to the alloy of Type II, as forged, and Photographs 40 and 41 refer to the same alloy as annealed after forging. They show the same two constituents as do the preceding bronzes.

Photographs 42 and 43, Plate XII, show the development of the same structure after quenching from 900° and reannealing at 600°.

III. Cupro-Aluminium, Type III

Plates XIII–XVII inclusive refer to Type III alloy, and show that quenching, whatever the temperature from

which this takes place, has no influence on the microstructure.

As we have seen, this alloy does not possess any transformation points, and shows the same microstructure after annealing, after quenching, and after quenching followed by reannealing.

.PPENDIX I

SIS OF ALUMINIUM

INIUM, SILICON, AND IRON IN COMMERCIAL

nium.

metal in 100 c.c. hydrochloric acid (1 : 3) ı solution is complete, transfer the liquid evaporate to dryness on a sand bath—to le.

oncentrated hydrochloric acid and 100 c.c. aluminium salts are completely dissolved; ›cting the filtrate in a graduated flask of to cool, and make up to the mark with ›he liquid into a flat-bottomed flask of shake vigorously to make the mixture

ıted pipette, transfer 200 c.c. of the liquid ı 1–2 c.c. of nitric acid, and boil for some lise the iron. Add excess of ammonia and l of ammonia has completely disappeared, lrops of ammonia and filter. Wash the h hot distilled water, dry and ignite.

·n, the oxides of iron and aluminium may salts. To remove these, powder the oxides ırder to avoid loss, it is necessary to moisten taining a few drops of ammonia. Filter, ɔngly for a quarter of an hour in a platinum ɜsed air Méker burner. Allow to cool in h rapidly—calcined alumina being very

ained, represents the total weight of the ninium. From this weight, subtract the estimated by the method given below, and of alumina.

)$_3 \times 0{\cdot}5302$ = aluminium).

: silica with hydrofluoric and sulphuric

(b) *Estimation of Iron.*

Act upon 2 gm. of the metal with 30 c.c. of 35 % soda (NaOH) in a conical flask, first in the cold, then on a sand bath, until all the aluminium is dissolved. Allow to settle, decant carefully, transfer to a filter with distilled water and wash.

By means of a jet of water, transfer the oxide of iron to a conical flask; dissolve by the addition of a few cubic centimetres of sulphuric acid; reduce by means of zinc, and titrate against permanganate of potash.

II. Method using Potash.

Place 1 gm. of aluminium in a conical flask with 10 c.c. of soda or potash (NaOH, KOH). Allow the reaction to take place in the cold, heating when it is nearly completed. Dilute to about 100 c.c. and filter.

The solution contains the zinc and aluminium, part of the tin and part of the silica. The residue consists of iron, copper, nickel, manganese, and magnesium, either as metal or oxide. This is washed and treated with dilute nitric acid and a little sulphuric acid. If tin is present, evaporate to dryness, take up, filter, wash the oxide of tin, and ignite. This is only part of the tin.

The filtrate is subjected to electrolysis to estimate the copper, and then boiled, and ammonia is added to precipitate the iron as oxide. The precipitate is dissolved in sulphuric acid, reduced by zinc, and the iron is estimated by titration against potassium permanganate.

Nickel is estimated by electrolysis of the ammoniacal filtrate.

Finally, if any magnesium is present, it is estimated by precipitation with sodium phosphate.

The initial potash solution contains a portion of the tin. Acidify with hydrochloric acid, pass in sulphuretted hydrogen, filter and wash. Treat the precipitate with nitric acid, ignite, weigh, and add this weight to that of the tin previously determined.

If any zinc is present, boil the acid filtrate from the sulphides, neutralise in the cold with sodium carbonate and sodium acetate, and pass in sulphuretted hydrogen—this causes the precipitation of zinc sulphide. Filter, wash, and redissolve in dilute sulphuric acid. Boil the solution, allow to cool, add ammonia and ammonium oxalate, and electrolyse.

All the other metals having been accurately determined, aluminium is usually obtained by difference.

If a direct determination of aluminium is desirable, as a check, the potash solution is neutralised with hydrochloric acid, and boiled for about 10 mins. The precipitated alumina is washed by decantation, filtered, redissolved in nitric acid, reprecipitated by ammonia under the same conditions, ignited, and weighed.

Silica.

Treat 1 gm. of aluminium with 30 c.c. of the following mixture :—

Nitric acid (1·42)	100 parts
Hydrochloric acid (1·2) . . .	100 parts
Sulphuric acid (25 % by volume) .	600 parts

in a vessel covered with a funnel, evaporate to dryness on a water bath, then on a sand bath until white fumes are given off. Take up with water, filter and wash. Fuse the precipitate, which consists of silicon and silica, with an equal weight of a mixture of sodium carbonate and potassium carbonate.

Take up with dilute hydrochloric acid, evaporate to dryness, filter, wash, ignite, and weigh. The silicon has been converted to silica.

III. Estimation of Alumina in Aluminium.

Outline of Method.

Pass a current of pure, dry chlorine over aluminium heated to 500°, to convert the elements aluminium, iron, silicon, and copper to chlorides, and leave the alumina and carbon unattacked. The volatile chlorides are driven off, and the others, if present, are separated by washing.

Details of Method.

(*a*) The apparatus consists of a source of pure, dry chlorine, preferably a bottle of liquid chlorine, a bubbling flask containing sulphuric acid, so that the rate of delivery can be regulated, a hard glass tube, of 30 mm. internal diameter and 60 mm. long, with one end bent and dipping into an empty flask. The combustion tube is heated in a gas furnace.

(*b*) For analysis, take 1 gm. of fragments or coarse shavings of the metal with clean surface and not powder or dust of which the surface is oxidised—the mere use of aluminium is sufficient to oxidise it.

The sample is placed in a large porcelain or silica boat, previously weighed, and introduced into the glass tube which has been thoroughly dried.

(*c*) Pass a rapid current of chlorine for a quarter of an hour, so as to displace completely the air which is in the apparatus. Warm gradually to dull redness, maintaining a steady current of gas, watch the boat, and, as soon as the incandescence, which marks the commencement of the reaction, is visible, increase the current of chlorine so as to drive to the exit all the aluminium chloride vapour. When the incandescence has ceased, reduce the current of chlorine, but allow it to pass for another half-hour, maintaining the temperature at dull redness.

At the end of this period, stop heating and allow the apparatus to cool in a current of the gas; when the tube is cold, the boat is removed and weighed; the increase in weight represents the alumina and carbon. The boat is then heated to redness to ignite the carbon, and after cooling weighed to give the weight of alumina, which should be white if pure.

APPENDIX II

Extracts from the French Aeronautical Specifications dealing with Aluminium and Light Alloys of great Strength

THE French Aeronautical Specifications* (8th April, 1919) prescribe the following methods for determining the physical and mechanical properties of aluminium and its alloys.

Pure Aluminium (Sheet and Strip).

Tensile and cupping tests are required.

Light Alloys of Great Strength.

While the composition and manner of working are left to the choice of the manufacturer, the density must not exceed 2·9, and the mechanical properties must be those specified below. The tests prescribed depend upon the form in which the metal is supplied, and are as follows :—

(i) Sheet and Strip : Tensile and cold bending tests.
(ii) Tubes : Drifting, crushing, and tensile tests.
(iii) Bars and Sections : Tensile tests only.

TENSILE TESTS.

Longitudinal and transverse tensile tests are prescribed in the case of aluminium and aluminium alloys of great strength of thickness greater than 1 mm., and involve the determination of Elastic Limit, Tensile Strength, and % Elongation.

The *Elastic Limit* is defined as the Stress, above which the Elongation is permanent, and is determined

(1) by means of a Stress/Strain diagram, if possible, giving an accuracy of ±1 % in the determination of the yield point and of the Elongation, or
(2) by means of dividers, or
(3) by means of the fall or arrest of the mercury column or of the arrow indicating the load.

* The Commission de Standardisation of the French Minister of Commerce (Commission A), unification des Cahiers des charges des produits métallurgiques (Aluminium and Light Alloys Section under the presidency of Lt.-Col. Grard) has drawn up the French General Specifications (Cahiers des Charges Unifiés Français) referring to aluminium and its alloys, for which the aeronautical specifications have served as a basis. Footnotes are given where any difference exists between the two specifications.

If dividers are used, the points are placed in two gauge marks on the test piece, and the load is noted at which the points of the dividers no longer reach the marks.

The *Tensile Strength* is defined as the maximum stress supported by the test piece before fracture takes place.

The Stress, in both Tensile Strength and Elastic Limit determinations, is calculated per unit area of cross section of the unstrained test piece, and is expressed in kilograms per square millimetre.

The *Elongation* is measured after fracture, by placing the two ends in contact and measuring the final distance apart of the gauge marks.

The gauge marks are punched on the unstrained test piece, the initial distance between them being given by the formula

$L = \sqrt{66{\cdot}67S}$ where L = gauge length (mm.)
S = initial area of cross section (sq. mm.)
66·67 = constant.

This length L should be marked out on the test piece in two separate places, from each end of the parallel portion.

The *Dimensions of the Test Pieces* for sheet and strip metal should be as follows :—

"NORMAL" TEST PIECES.

Between shoulders. Length, 200 mm.
Breadth, 30 mm.
Thickness, that of the sheet or strip.

Ends. Length, 50 mm.
Breadth, 40 mm.

Curved portion of shoulders, 10 mm. radius.

These dimensions may be diminished, but the length between shoulders must be equal to the gauge length specified plus twice the breadth of the test piece.

REQUIREMENTS.

(1) *Pure Aluminium, Sheet and Strip.*

The following values should be obtained :—

(*a*) Longitudinal. Tensile Strength (minimum), 9 kg./mm.^{2} (5·7 tons/in.^{2})
% Elongation, 38 %

(*b*) Transverse. Tensile Strength (minimum), 9 kg./mm.^{2} (5·7 tons)
% Elongation, 36 %.

But, in both cases, if the Tensile Strength exceeds that specified (9 kg./mm.^{2}) by n kg./mm^2, then the value of the % Elongation,

which will be required, will be lower than that specified by 2n %, provided that the value is not below 32 %.

Example. Longitudinal test piece—

Tensile Strength (observed) =10·5.
Then % Elongation required =38—2(1·5) =35 %.

(2) *Light Alloys of Great Strength.*

The following values are required :—

Sheet and Strip.

Tensile Strength	=38 kg. per sq. mm.* (24·1 tons/in.^{2})
Elastic Limit	=20 kg. per sq. mm. (12·7 tons/in.^{2})
% Elongation	=14.

Tubes. Tensile tests are carried out on the actual tubes, using steel plugs to avoid local cracking during the test. In the case of tubes of diameter greater than 30 mm., and of tubes not cylindrical, the tube is cut longitudinally, flattened out by means of a wooden mallet, and a test piece is cut to the dimensions specified.

The values required are :—

Minimum Tensile Strength :	36 kg. per sq. mm. (22·8 tons/in.^{2})
Elastic Limit :	20 kg. per sq. mm. (12·7 tons/in.^{2})
% Elongation :	15 %.

Bars and Sections. The requirements are as follows :—

Class (*a*). Sections $\geqq$ 2 mm. thick.
Bars $\geqq$ 16 mm. in diameter and < 36 mm. in diameter.

Tensile Strength :	36 kg. per sq. mm. (22·8 tons/in.^{2})
Elastic Limit :	20 kg. per sq. mm. (12·7 tons/in.^{2}).

For bars > 36 mm. in diameter :—

Tensile Strength :	33 kg. per sq. mm. (20·9 tons/in.^{2})
Elastic Limit :	19 kg. per sq. mm. (12·1 tons/in.^{2})
% Elongation :	13 %.

Class (*b*). Sections < 2 mm. thick.
Bars (specified *Drawn*) of any diameter and bars < 16 mm. in diameter.

Tensile Strength :	38 kg. per sq. mm. (24·1 tons per sq. in.)
Elastic Limit :	22 kg. per sq. mm. (14·0 tons per sq. in.)
% Elongation :	16 %, or 14 % in the case of bars and sections so thin that straightening is necessary.

CUPPING TESTS.

Cupping tests are required for pure aluminium, sheet and strip. The prescribed method is that described on page 41, and the

* The Cahiers des Charges Unifiés Français specify a minimum Tensile Strength of 36 kg./mm.^{2} (22·8 tons/in^2.).

following minimum depth of impression at rupture should be obtained :—

Thickness . .	0·5 mm. ·020 in.	1·0 mm. ·039 in.	1·5 mm. ·059 in.	2·0 mm. ·079 in.
Depth of impression .	11 mm.	13 mm.	14 mm.	15 mm.

Cold Bending Tests are prescribed for light alloy sheet and strip, and the following method should be adopted wherever possible :—

The test is carried out at ordinary temperatures, and in a special machine giving a gradually increasing pressure, without shock. The bend is formed in two operations.

First Operation. The test piece, which should be 100 mm.× 20 mm. if possible, is placed on a V-shaped block, whose surfaces are inclined to each other at an angle of 60° ; the opening should be 125 mm. at least. A wedge (whose edge should be rounded off with a radius at least equal to that which the bend should have at the completion of the test) is applied to the middle of the test piece, and depressed mechanically until the test piece is in contact with the faces of the V.

Second Operation. Using a spacer, the test piece should be bent slowly, by mechanical means, into the form of the letter U. No cracks should appear. The distance between the two interior surfaces of the arms of the U is specified in the following table :—

*Thickness.**	*Longitudinal.*	*Transverse.*
Less than 1·5 mm. (·059 in.)	$3\frac{1}{2}$ × thickness	4 × thickness
= or > 1·5 mm. (·059 in.)	4 × thickness	5 × thickness

Drifting Tests. Prescribed for light alloy tubes.

A conical, hardened steel mandrel, having an angle of 45°, is forced axially into a short length of tube until the first split appears. This should not occur until the diameter has increased by 11 %.†

Crushing Tests. Prescribed for light alloy tubes.

A short length of tube is flattened by means of a hammer moving in a direction parallel to the principal axis. The tube is supported on a piece of steel to avoid localisation of stress. No fissure should appear until the reduction in length of the principal axis of the tube has reached or exceeded 40 %.

* The Cahiers des Charges Unifiés Français specify the following distances :

Thickness.	Longitudinal.	Transverse.
< 1·5 mm.	4·5 × thickness	5 × thickness
= or > 1·5 mm.	5·5 × thickness	6 × thickness

† Cahiers Unifiés Français specify 9 %.

APPENDIX III

LABORATOIRE D'ESSAIS MÉCANIQUES, PHYSIQUES, CHIMIQUES ET DE MACHINES.
292 *Rue Saint Martin, Paris.*

RÉPUBLIQUE FRANÇAISE.
Ministère du Commerce, de l'Industrie, des Postes et des Télégraphes.

Conservatoire des Arts et Métiers.

Paris, Feb. 5th, 1919.

Report of Test No. 13456 on the requisition of Major Grard, technical inspector of metallurgical aviation materials, Paris.

Registered, Jan. 18th, 1919.

Object. Tensile and Shock tests at a temperature of 15° on test pieces of sheet aluminium possessing various degrees of cold work.

RESULTS.

Dimensions of test pieces.

(a) *Tensile Test Pieces.*

Between shoulders	Length . . .	100 mm.
	Breadth . . .	15 mm.
	Thickness . . .	10 mm.
Approximate area of cross section . . (accurately measured for each test piece)		150 sq. mm.
Gauge length $=\sqrt{66{\cdot}67S}$ . . .		= 100 mm.

(b) *Shock Test Pieces.*

Bars : $55\times10\times10$ mm. with a 2·mm. round notch.
Apparatus : 30 kg. m. Charpy pendulum.

State of Metal*	Direction of cutting test pieces*	Marks†		Tensile Tests: Apparent Elastic Limit Kg/mm²	Apparent Elastic Limit tons/in²	Tensile Strength Kg/mm²	Tensile Strength tons/in²	Elongation %	$\frac{S-s}{S}$ Reduction	Brinell Hardness (10 mm. ball) 1000 Kg. Diam. (mm.)	1000 Kg. Hardness	500 Kg. Diam. (mm.)	500 Kg. Hardness	Shock Tests: Shock Resistance Kg.m/cm²	Angle of Rupture‡
Annealed	Longitudinal	A1	1	3·9	2·48	9·9	6·29	36·0	66	6·90	23·0	5·05	23·3	8·3	×
			2	4·0	2·54	10·0	6·35	37·0	66	6·90	23·0	5·10	22·8	8·3	×
			3	3·9	2·48	9·9	6·29	36·7	65	6·85	23·4	5·10	22·8	8·3	×
			4	4·2	2·67	9·9	6·29	35·0	68	6·90	23·0	5·10	22·8	8·5	×
			5	4·0	2·54	10·0	6·35	37·2	69	6·85	23·4	5·10	22·8	8·3	×
			6	3·7	2·36	10·0	6·35	39·2	69	6·80	23·8	5·10	22·8	8·5	×
	Transverse	A1	7	3·5	2·22	9·8	6·22	31·5	64	6·85	23·4	5·15	22·3	8·3	×
			8	3·4	2·16	9·7	6·16	31·2	61	6·95	22·6	5·20	21·8	8·3	×
			9	3·4	2·16	9·7	6·16	31·4	66	6·95	22·6	5·15	22·3	7·3	×
			10	3·5	2·22	9·8	6·22	30·2	63	6·90	23·0	5·10	22·8	8·3	×
			11	3·4	2·16	9·7	6·16	33·0	69	6·95	22·6	5·10	22·8	8·3	×
			12	3·9	2·48	9·6	6·10	28·0	64	6·90	23·0	5·10	22·8	8·3	×
Cold worked 50 %	Longitudinal	A2	13	11·7	7·43	14·3	9·08	8·5	53	5·70	35·6	4·10	36·0	5·0	×
			14	11·8	7·49	14·3	9·08	8·0	44	5·70	35·6	4·10	36·0	4·5	×
			15	12·7	8·07	14·4	9·15	8·7	50	5·65	36·4	4·05	37·0	4·6	×
			16	12·1	7·68	14·3	9·08	8·2	45	5·70	35·6	4·05	37·0	4·6	×
			17	12·7	8·07	14·3	9·08	8·5	50	5·70	35·6	4·10	36·0	4·4	×
			18	12·8	8·13	14·3	9·08	8·2	49	5·70	35·6	4·10	36·0	5·1	×
	Transverse	A2	19	12·4	7·87	13·9	8·83	10·0	52	5·75	35·0	4·10	36·0	5·0	×
			20	12·4	7·87	13·8	8·76	9·6	51	5·70	35·6	4·20	34·5	5·0	×
			21	12·3	7·81	13·7	8·70	7·5	43	5·70	35·6	4·10	36·0	5·2	×
			22	12·5	7·94	13·8	8·76	9·0	50	5·75	35·0	4·10	36·0	5·4	×
			23	12·6	8·00	13·9	8·83	9·0	48	5·70	35·6	4·05	37·0	5·0	×
			24	12·6	8·00	13·9	8·83	10·0	46	5·75	35·0	4·15	35·0	5·1	×

Cold worked 100 %	Longitudinal	A3	25	13·1	8·32	14·6	9·27	8·2	43	5·50	38·6	3·95	39·0	5·2	×
			26	13·2	8·38	14·8	9·40	8·2	39	5·50	38·6	3·90	40·0	4·5	×
			27	13·4	8·51	14·9	9·46	9·5	42	5·60	37·6	3·90	40·0	4·6	×
			28	13·5	8·57	15·0	9·53	9·0	42	5·45	39·4	3·95	39·0	4·5	×
			29	13·1	8·32	14·7	9·33	10·0	40	5·30	38·6	3·90	40·0	5·2	×
			30	13·3	8·45	14·8	9·40	8·3	40	5·60	37·6	3·95	39·0	4·6	×
	Transverse	A3	31	13·1	8·32	15·3	9·72	8·0	44	5·50	38·6	3·90	40·0	4·5	×
			32	12·6	8·00	15·4	9·78	7·4	37	5·45	39·4	3·90	40·0	5·1	×
			33	13·3	8·45	15·3	9·72	7·0	38	5·50	38·6	3·90	40·0	4·5	×
			34	13·2	8·38	15·2	9·65	8·8	40	5·50	38·6	3·90	40·0	4·5	×
			35	13·7	8·70	15·3	9·72	8·0	41	5·45	39·4	3·90	40·0	4·2	×
			36	—	—	—	—	—	—	—	—	—	—	4·0	×
Cold worked 200 %	Longitudinal	A4	37	13·7	8·70	15·6	9·91	8·0	36	5·45	39·4	3·90	40·0	4·9	×
			38	14·3	9·08	15·5	9·84	7·1	34	5·45	39·4	3·95	39·0	4·6	×
			39	14·2	9·02	15·8	10·03	8·9	40	5·40	40·2	3·85	41·0	4·8	×
			40	13·8	8·76	15·6	9·91	8·5	43	5·45	39·4	3·80	43·0	4·8	×
			41	14·8	9·40	15·8	10·03	8·5	44	5·35	41·2	3·80	43·0	5·1	×
			42	12·6	8·00	15·7	9·97	9·5	49	5·45	39·4	3·90	40·0	4·6	×
	Transverse	A4	43	14·7	9·33	16·3	10·35	7·1	38	5·40	40·2	3·80	43·0	3·3	25°
			44	14·3	9·08	16·4	10·41	6·9	34	5·45	39·4	3·80	43·0	4·1	39°
			45	14·7	9·33	16·3	10·35	7·5	42	5·35	41·2	3·75	44·0	3·3	33°
			46	13·9	8·83	16·1	10·22	7·0	40	5·40	40·2	3·80	43·0	4·1	39°
			47	14·0	8·89	16·3	10·35	7·5	41	5·40	40·2	3·80	43·0	3·2	30°
			48	14·7	9·33	16·2	10·29	6·0	35	5·35	41·2	3·80	43·0	3·0	24°
Cold worked 300 %	Longitudinal	A5	49	14·1	8·95	15·2	9·65	9·0	46	5·50	38·6	4·10	36·0	4·5	×
			50	13·3	8·45	14·9	9·46	9·2	40	5·60	38·0	3·95	39·0	6·0	×
			51	13·3	8·45	14·8	9·40	9·0	49	5·65	37·6	3·95	39·0	6·0	×
			52	12·8	8·13	15·0	9·53	8·8	43	5·60	38·6	3·90	40·0	5·2	×
			53	13·4	8·51	15·3	9·72	10·0	43	5·60	38·0	3·95	39·0	6·0	×
			54	13·0	8·25	15·0	9·53	9·0	42	5·55	38·0	4·00	38·0	6·0	×
	Transverse	A5	55	14·3	9·08	15·2	9·65	7·5	41	5·30	38·6	3·95	39·0	3·2	×
			56	14·6	9·27	15·4	9·78	8·0	48	5·55	38·0	3·90	40·0	4·6	×
			57	14·5	9·21	15·4	9·78	7·0	38	5·60	37·6	3·90	40·0	2·7	×
			58	13·3	8·45	15·2	9·65	8·0	44	5·50	38·6	3·90	40·0	3·1	×
			59	14·7	9·33	15·4	9·78	6·1	36	5·55	38·0	3·98	40·0	3·7	×
			60	14·2	9·02	15·3	9·72	7·1	37	5·55	38·0	3·90	40·0	—	×

* Information given to the laboratory. † Same marks for tensile and shock test pieces. ‡ × denotes unbroken bars.

(Signed) F. Cellerier, Major, Director of the Testing Laboratories.

APPENDIX IV

LABORATOIRE D'ESSAIS MÉCANIQUES, PHYSIQUES, CHIMIQUES ET DE MACHINES.

RÉPUBLIQUE FRANÇAISE.
Ministère du Commerce, de l'Industrie, des Postes et des Télégraphes.
Conservatoire des Arts et Métiers.
Paris, Jan. 24th, 1919.

Report, No. I, of Test No. 13357 on the requisition of Major Grard, technical inspector of metallurgical aviation materials, Paris.

Registered, Nov. 27th, 1918.

Object. Tensile tests on test pieces of sheet aluminium after thermal treatment.

NATURE OF SAMPLES SUBMITTED.

Two series of tensile test pieces in sheet aluminium :—

(1) 0·5 mm. thick marked 5.
(2) 2·0 mm. thick marked 20.

Each of these series consists of metal having three degrees of cold work, namely :—

50 % marked B.
100 % marked C.
300 % marked D.

Metal of each of the above thicknesses and degrees of cold work has been annealed under the following conditions :—

All the test pieces requiring the same anneal were pierced with a hole at one end and threaded on to the same piece of wire, 6–8 mm. apart, so as to be immersed simultaneously in the annealing bath, which was continuously stirred.

Sheets 40 mm. square and circles 90 mm. in diameter, for micrographic examination and cupping tests respectively, were subjected to the same anneal at the same time as the tensile test pieces.

RESULTS.

Dimensions of Test Pieces.

Between shoulders	Length . .	100 mm.
	Breadth . .	20 mm.

Approximate area of cross section :—*

(1) Test pieces 0·5 mm. thick . . 10 sq. mm.
(2) Test pieces 2·0 mm. thick . . 40 sq. mm.

Gauge length $=\sqrt{66 \cdot 67 S}$:—

(1) Test pieces 0·5 mm. thick—gauge length =30 mm.
(2) Test pieces 2·0 mm. thick—gauge length =50 mm.

* In each case the breadth and thickness were measured to the nearest ·01 mm., and the exact cross section calculated from these figures.

VARIATION IN TEMPERATURE ABOUT THE REQUIRED TEMPERATURE DURING THE COURSE OF THE EXPERIMENT

Anneal	Bath	Duration (minutes)	Required temperature (degrees C.)	Temperature after . . . . . . minutes (degrees C.) 0	0·5	1	2	3	4	5	6	7	8	9	10	Mean temperature (degrees C.)
Preliminary	Oil	2	200	206	—	202	201	—	—	—	—	—	—	—	—	203·0
		5		207	—	207	208	—	210	210	—	—	—	—	—	208·5
		10		207	—	204	204	—	204	203	203	203	202	203	203	203·5
	Salt	1	400	400	399	395	—	—	—	—	—	—	—	—	—	398·0
		3		402	400	400	405	408	—	—	—	—	—	—	—	403·0
		5		411	409	408	388	380	382	388	—	—	—	—	—	393·0
		0·5	550	549	549	—	—	—	—	—	—	—	—	—	—	549·0
		1		550	549	551	—	—	—	—	—	—	—	—	—	550·0
		2		558	552	550	549	—	—	—	—	—	—	—	—	551·0
Final	Oil	5	100	102	101	102	103	104	105	106	—	—	—	—	—	103·0
			150	153	151	150	149	149	149	148	—	—	—	—	—	150·0
			200	201	199	198	199	199	199	198	—	—	—	—	—	199·0
			250	250	245	244	243	243	244	245	—	—	—	—	—	244·0
			300	304	301	299	298	298	297	297	—	—	—	—	—	299·0
	Salt	3	350	358	355	353	353	353	—	—	—	—	—	—	—	354·0
			400	420	410	410	410	410	—	—	—	—	—	—	—	411·0
			450	460	453	450	450	450	—	—	—	—	—	—	—	452·0
			500	510	498	492	492	492	—	—	—	—	—	—	—	496·0
		1	550	560	550	548	—	—	—	—	—	—	—	—	—	552·0
			600	613	600	600	—	—	—	—	—	—	—	—	—	604·0

A. PRELIMINARY TESTS *

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)	Marks		Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	Remarks
203·0°	2	5	B1	11·1	7·05	12·7	8·06	6·0	(2)
			B2	11·3	7·18	13·7	8·70	12·7	(2)
			C1	10·4	6·60	14·2	9·02	12·7	
			C2	11·0	6·98	15·1	9·59	16·3	
			D1	11·5	7·80	15·8	10·03	6·0	(1)
			D2	10·4	6·60	15·9	10·09	4·0	(1)
		20	B1	9·8	6·22	11·9	7·56	16·4	
			B2	9·45	6·00	11·4	7·24	15·0	
			C1	6·85	4·35	12·8	8·23	16·6	
			C2	8·65	5·49	13·0	8·26	15·0	
			D1	13·2	8·35	15·4	9·78	10·0	
			D2	12·9	8·19	15·2	9·65	9·8	
208·5°	5	5	B3	11·5	7·30	13·5	8·57	16·0	(1)
			B4	9·9	6·29	13·2	8·38	11·6	
			C3	12·0	7·62	13·9	8·83	16·6	
			C4	12·3	7·81	14·4	9·14	16·0	
			D3	13·3	8·45	15·8	10·03	10·0	
			D4	13·3	8·45	15·7	9·97	10·0	
		20	B3	9·6	6·10	11·5	7·30	16·0	
			B4	9·4	5·97	12·1	7·68	16·0	
			C3	10·2	6·48	12·8	8·13	16·0	
			C4	10·9	6·92	12·8	8·13	17·4	
			D3	11·9	7·56	14·7	9·30	10·0	
			D4	11·0	6·98	14·8	9·40	10·0	(1)
203·5°	10	5	B5	11·0	6·98	13·2	8·38	12·7	(1)
			B6	11·7	7·43	15·3	9·72	16·0	
			C5	10·8	6·86	14·3	9·08	15·0	
			C6	10·7	6·79	15·5	9·84	16·0	
			D5	11·0	6·98	16·3	10·35	11·7	
			D6	14·0	8·89	15·5	9·84	9·7	
		20	B5	10·1	6·41	11·9	7·56	18·2	
			B6	9·1	5·78	11·8	7·49	18·2	
			C5	10·9	6·92	12·7	8·06	17·0	
			C6	11·6	7·37	12·7	8·06	18·8	
			D5	12·4	7·87	14·7	9·33	10·0	
			D6	11·5	7·30	15·0	9·52	11·8	

* These tests have been carried out with a view to investigating the minimum length of time necessary for complete anneal at any given temperature, using test pieces of any given thickness.

As a result of these preliminary tests, the following experimental conditions have been adopted for both types of test piece:

Temperature and anneal.	Duration (minutes).
150°—300°(inclusive)	5
350°—500° ,,	3
550°—600° ,,	1

Remarks.—(1) Broken outside gauge length.
(2) Broken on gauge mark.

A. Preliminary Tests—*continued*

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)	Marks		Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	Remarks
398°	1	5	B7	5·5	3·49	11·2	7·11	35·0	
			B8	3·9	2·48	10·8	6·86	31·7	
			C7	4·1	2·60	12·5	7·94	33·4	(2)
			C8	4·3	2·73	12·1	7·68	40·0	
			D7	4·4	2·79	11·8	7·49	36·6	
			D8	3·8	2·41	12·0	7·62	36·0	
		20	B7	3·4	2·16	9·8	6·22	38·6	
			B8	3·6	2·29	9·9	6·29	38·0	
			C7	3·5	2·22	10·2	6·48	37·4	
			C8	3·0	1·90	10·2	6·48	44·0	
			D7	3·1	1·97	10·6	6·73	40·0	
			D8	3·4	2·16	10·6	6·73	37·0	
403°	3	5	B9	5·2	3·30	10·1	6·41	34·4	
			B10	4·3	2·73	10·9	6·92	33·3	
			C9	5·4	3·43	11·2	7·11	36·4	
			C10	5·2	3·30	11·8	7·49	36·7	
			D9	4·0	2·54	11·6	7·37	35·0	
			D10	4·7	2·98	11·7	7·43	38·4	
		20	B9	3·1	1·97	9·7	6·16	38·6	
			B10	3·0	1·90	9·7	6·16	36·8	
			C9	3·0	1·90	10·4	6·60	40·4	
			C10	2·6	1·65	10·4	6·60	38·4	
			D9	3·4	2·16	10·8	6·86	38·0	
			D10	3·6	2·29	10·8	6·86	36·4	
393°	5	5	B11	5·1	3·24	11·5	7·30	36·0	
			B12	4·8	3·05	11·4	7·24	33·3	
			C11	4·9	3·11	11·7	7·43	34·0	
			C12	5·3	3·37	12·2	7·75	38·4	
			D11	3·4	2·16	11·4	7·24	38·4	
			D12	3·6	2·29	11·5	7·30	37·0	
		20	B11	3·1	1·97	9·6	6·10	39·0	
			B12	2·9	1·84	9·7	6·16	39·0	
			C11	3·4	2·16	10·6	6·73	39·4	
			C12	4·2	2·67	10·8	6·86	41·0	
			D11	3·6	2·29	10·7	6·79	36·0	
			D12	3·8	2·41	10·8	6·86	36·4	
549°	0·5	5	B13	3·9	2·48	11·6	7·37	33·3	
			B14	3·3	2·10	11·5	7·30	32·6	
			C13	4·2	2·67	11·8	7·49	36·8	
			C14	3·4	2·16	11·7	7·43	36·8	
			D13	3·2	2·03	11·1	7·05	38·4	
			D14	3·8	2·41	11·2	7·11	36·8	
		20	B13	2·8	1·78	9·9	6·29	39·6	
			B14	3·1	1·97	10·2	6·48	38·0	
			C13	3·2	2·03	11·1	7·05	37·8	
			C14	3·6	2·29	10·8	6·86	34·0	
			D13	3·1	1·97	10·9	6·92	39·6	
			D14	3·3	2·10	10·9	6·92	37·0	

A. Preliminary Tests—*continued*

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)	Marks		Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	Remarks
550°	1	5	B15	4·2	2·67	11·2	7·11	34·4	
			B16	4·1	2·60	11·0	6·98	34·4	
			C15	4·8	3·05	11·7	7·43	35·0	
			C16	3·8	2·41	12·3	7·81	31·7	
			D15	3·7	2·35	12·0	7·62	34·4	
			D16	5·0	3·17	11·6	7·34	35·0	
		20	B15	2·9	1·84	10·2	6·48	38·6	
			B16	2·8	1·78	10·0	6·35	36·0	
			C15	3·3	2·10	11·0	6·98	32·0	
			C16	3·4	2·16	11·3	7·18	36·0	
			D15	3·2	2·03	10·9	6·92	39·0	
			D16	3·1	1·97	10·8	6·86	35·6	
551°	2	5	B17	5·0	3·17	11·8	7·49	33·3	
			B18	4·8	3·05	12·2	7·75	32·7	
			C17	5·0	3·17	13·2	8·38	33·3	
			C18	4·7	2·98	11·9	6·56	30·0	
			D17	4·4	2·79	11·5	7·30	35·0	
			D18	4·4	2·79	11·8	7·49	37·4	
		20	B17	2·9	1·84	10·1	6·41	35·6	
			B18	2·6	1·65	9·9	6·29	36·6	
			C17	2·8	1·78	11·3	7·18	35·6	
			C18	3·2	2·03	11·2	7·11	35·0	
			D17	3·3	2·10	11·0	6·98	36·0	
			D18	3·4	2·16	11·0	6·98	41·6	

B. Final Experiments

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)	Marks		Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	Remarks
Zero metal unannealed		5	B64	13·4	8·51	13·9	8·83	6·7	
			B65	13·1	8·32	14·5	9·21	9·7	
			B66	13·3	8·45	14·6	9·27	12·7	
			C64	14·3	9·08	15·1	9·59	11·7	
			C65	14·4	9·14	15·4	9·78	12·3	
			C66	13·8	8·76	15·4	9·78	10·0	(1)
			D64	17·3	10·99	17·3	10·99	3·3	(1)
			D65	17·0	10·79	17·0	10·79	6·0	
			D66	17·8	11·30	17·8	11·30	6·3	
		20	B64	11·5	7·30	12·0	7·62	10·0	
			B65	11·4	7·24	12·2	7·75	11·0	
			B66	11·4	7·24	12·4	7·87	10·6	
			C64	13·1	8·32	13·7	8·70	14·4	
			C65	12·8	8·13	13·8	8·76	11·2	
			C66	13·0	8·25	13·4	8·51	11·6	
			D64	15·8	10·03	16·3	10·35	7·0	
			D65	15·9	10·10	16·6	10·54	8·0	
			D66	15·5	9·84	17·2	10·92	6·6	

B. Final Experiments—*continued*

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)		Marks	Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	Remarks
103°	5	5	B31	12·9	8·19	14·0	8·89	12·7	
			B32	13·8	8·76	13·8	8·76	13·0	
			B33	13·1	8·32	15·4	9·78	13·3	
			C31	14·8	9·40	14·8	9·40	11·7	
			C32	14·5	9·21	15·0	9·52	10·0	
			C33	14·2	9·02	14·6	9·27	8·3	(1)
			D31	17·1	10·87	17·6	11·18	6·0	
			D32	15·4	9·78	15·4	9·78	3·3	
			D33	16·9	10·73	17·3	10·99	5·0	(1)
		20	B31	11·5	7·30	12·0	7·62	13·6	
			B32	11·1	7·05	12·0	7·62	14·0	
			B33	11·1	7·05	12·0	7·62	12·0	
			C31	12·1	7·68	13·5	8·57	14·6	
			C32	12·4	7·87	13·7	8·70	10·0	(1)
			C33	12·4	7·87	13·6	8·64	13·0	
			D31	14·9	9·46	16·0	10·16	7·6	(1)
			D32	13·9	8·83	15·8	10·03	6·0	(1)
			D33	13·7	8·70	16·0	10·16	6·0	(1)
150°	5	5	B34	12·1	7·68	13·4	8·51	13·3	
			B35	13·8	8·76	13·6	8·64	15·0	
			B36	13·0	8·25	13·48	8·56	15·0	
			C34	10·4	6·60	14·7	9·33	10·0	
			C35	13·5	8·57	14·6	9·27	10·0	
			C36	12·9	8·19	14·9	9·46	6·3	(1)
			D34	12·5	7·94	16·13	10·24	3·3	(1)
			D35	13·9	8·83	14·5	9·21	3·3	(1)
			D36	12·3	7·81	14·9	9·46	3·3	(1)
		20	B34	10·6	6·73	12·1	7·68	13·6	
			B35	10·9	6·92	12·4	7·87	14·0	
			B36	10·6	6·73	12·0	7·62	13·6	
			C34	12·1	7·68	13·0	8·25	14·0	
			C35	11·7	7·43	13·1	8·32	15·0	
			C36	11·5	7·30	13·3	8·45	12·0	
			D34	12·9	8·19	15·4	9·78	8·2	
			D35	14·0	8·89	15·6	9·91	6·2	(1)
			D36	13·2	8·38	15·5	9·84	7·4	
199°	5	5	B37	12·0	7·62	12·2	7·75	15·3	
			B38	11·5	7·30	13·2	8·38	10·6	
			B39	11·8	7·49	13·2	8·38	10·4	(1)
			C37	13·0	8·25	14·4	9·14	10·0	(1)
			C38	13·4	8·51	15·2	9·65	15·0	(1)
			C39	13·4	8·51	14·1	8·95	7·7	
			D37	13·7	8·70	16·5	10·48	6·7	(1)
			D38	14·2	9·02	17·6	11·18	7·3	
			D39	13·5	8·57	17·0	10·79	5·0	(1)
		20	B37	9·6	6·10	11·5	7·30	16·2	
			B38	10·3	6·54	12·0	7·62	16·0	
			B39	10·0	6·35	11·6	7·37	16·2	
			C37	12·0	7·62	13·0	8·25	18·0	
			C38	12·0	7·62	13·2	8·38	16·4	
			C39	11·0	6·98	12·8	8·13	17·6	
			D37	13·8	8·76	15·4	9·78	10·0	
			D38	13·2	8·38	15·3	9·72	8·0	
			D39	13·9	8·83	15·3	9·72	9·0	

B. FINAL EXPERIMENTS—*continued*

Anneal Temperature (degrees C.)	Anneal Duration (minutes)		Marks	Apparent Elastic Limit Kg/mm²	Apparent Elastic Limit tons/in²	Tensile Strength Kg/mm²	Tensile Strength tons/in²	Elongation %	Remarks
244°	5	5	B40	11·6	7·37	13·5	8·57	19·3	
			B41	11·1	7·05	12·5	7·94	19·3	
			B42	11·2	7·11	13·4	8·51	20·0	
			C40	12·5	7·94	12·8	8·23	10·3	(1)
			C41	10·5	6·67	13·5	8·57	17·3	
			C42	11·8	7·49	13·3	8·45	19·3	
			D40	14·0	8·89	14·0	8·89	10·7	(1)
			D41	12·6	8·06	14·6	9·27	11·0	
			D42	14·7	9·33	15·3	9·72	12·0	
		20	B40	9·7	6·16	11·3	7·18	17·6	
			B41	10·2	6·48	11·3	7·18	18·0	
			B42	10·0	6·35	11·5	7·30	17·0	
			C40	11·7	7·43	12·6	8·00	21·8	
			C41	10·8	6·86	12·5	7·94	21·0	
			C42	11·2	7·11	12·3	7·81	22·0	
			D40	13·1	8·32	14·5	9·21	12·2	
			D41	12·2	7·75	14·4	9·14	12·0	
			D42	12·1	7·68	14·2	9·02	13·6	
299°	5	5	B43	10·8	6·86	13·1	8·32	27·3	
			B44	10·4	6·60	11·9	7·56	22·7	
			B45	9·6	6·10	12·1	7·68	23·3	
			C43	7·0	4·44	11·3	7·18	35·0	
			C44	6·3	4·00	10·7	6·79	33·3	
			C45	6·8	4·32	10·8	6·86	38·3	
			D43	5·9	3·68	10·2	6·48	39·3	
			D44	6·0	3·75	11·0	6·98	38·3	
			D45	6·5	4·13	10·9	6·92	41·9	
		20	B43	8·8	5·59	10·7	6·79	20·4	
			B44	8·8	5·59	10·6	6·73	23·6	
			B45	9·0	5·71	10·6	6·73	23·4	
			C43	5·7	3·56	10·4	6·60	33·0	
			C44	6·8	4·32	10·3	6·54	32·0	
			C45	5·9	3·68	10·3	6·54	34·0	
			D43	8·3	5·27	12·0	7·62	26·0	
			D44	7·9	5·01	12·0	7·62	26·0	
			D45	8·4	5·33	11·8	7·49	24·4	
354°	3	5	B46	5·3	3·37	11·1	7·05	35·0	
			B47	5·0	3·17	10·2	6·48	36·0	
			B48	6·1	3·87	10·8	6·86	33·3	
			C46	4·9	3·11	10·8	6·86	40·0	
			C47	4·4	2·79	10·6	6·73	29·7	
			C48	4·8	3·05	11·2	7·11	37·3	
			D46	4·6	2·92	10·8	6·86	41·6	
			D47	5·0	3·17	11·1	7·05	41·6	
			D48	5·6	3·49	10·9	6·92	39·0	
		20	B46	4·4	2·79	9·4	5·97	37·0	
			B47	4·5	2·86	9·4	5·97	34·0	
			B48	5·4	3·43	9·6	6·10	35·0	
			C46	4·3	2·73	9·9	6·29	44·0	
			C47	4·4	2·79	10·0	6·35	44·4	
			C48	4·9	3·11	10·0	6·35	44·4	
			D46	4·8	3·05	10·4	6·60	42·0	
			D47	4·4	2·79	10·9	6·92	41·0	
			D48	4·9	3·11	10·2	6·48	41·2	

B. Final Experiments—*continued*

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)	Marks		Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	Remarks
			B49	4·7	2·98	10·8	6·86	34·6	
			B50	5·5	3·49	10·9	6·92	32·7	
			B51	5·7	3·62	10·8	6·86	34·0	
			C49	4·8	3·05	10·9	6·92	36·6	
		5	C50	5·2	3·30	11·2	7·11	36·6	
			C51	5·2	3·30	11·1	7·05	38·3	
			D49	5·3	3·37	11·6	7·37	37·0	
			D50	5·5	3·49	11·0	6·98	38·4	
411°	3		D51	5·6	3·56	10·5	6·67	37·3	
			B49	4·4	2·79	9·7	6·16	38·0	
			B50	4·5	2·86	9·7	6·16	38·4	
			B51	4·4	2·79	9·6	6·10	38·4	
			C49	4·9	3·11	10·5	6·67	41·0	
		20	C50	5·1	3·24	10·6	6·73	39·6	
			C51	4·8	3·05	10·4	6·60	39·6	
			D49	5·1	3·24	10·7	6·79	38·0	
			D50	4·9	3·11	10·7	6·79	38·0	
			D51	5·0	3·17	10·7	6·79	37·6	
			B52	5·1	3·24	10·7	6·79	32·7	
			B53	5·1	3·24	10·9	6·92	35·0	
			B54	5·5	3·49	10·8	6·86	35·0	
			C52	5·5	3·49	11·3	7·18	36·7	
		5	C53	5·9	3·75	11·2	7·11	37·7	
			C54	5·7	3·62	11·6	7·37	35·0	
			D52	5·5	3·49	11·0	6·98	37·3	
			D53	5·2	3·30	11·1	7·05	36·7	
452°	3		D54	5·5	3·49	11·5	7·30	36·7	
			B52	3·4	2·16	10·1	6·41	37·6	
			B53	3·3	2·10	9·8	6·22	36·4	
			B54	3·6	2·29	9·5	6·03	36·4	
			C52	3·9	2·48	10·9	6·92	37·6	
		20	C53	4·5	2·86	10·9	6·92	37·2	
			C54	4·8	3·05	10·4	6·60	36·4	
			D52	3·9	2·48	11·0	6·98	36·0	
			D53	4·1	2·60	11·0	6·98	35·4	
			D54	4·6	2·92	11·1	7·05	37·8	
			B55	4·5	2·86	11·4	7·24	24·0	
			B56	5·3	3·37	11·2	7·11	33·3	
			B57	4·9	3·11	11·3	7·18	33·3	
			C55	4·1	2·60	10·9	6·92	33·3	
		5	C56	4·7	2·98	11·4	7·24	34·0	
			C57	4·6	2·92	11·1	7·05	37·4	
			D55	5·4	3·43	11·6	7·37	35·0	
			D56	6·4	4·06	11·3	7·18	37·6	
496°	3		D57	6·4	4·06	11·6	7·37	35·6	
			B55	3·5	2·22	9·6	6·10	37·6	
			B56	3·5	2·22	9·7	6·16	38·0	
			B57	3·4	2·16	9·8	6·22	35·0	
			C55	4·0	2·54	11·0	6·98	35·0	
		20	C56	3·6	2·29	10·5	6·67	37·2	
			C57	3·1	1·97	10·9	6·92	36·0	
			D55	4·6	2·92	11·3	7·18	35·4	
			D56	4·0	2·54	11·2	7·11	36·0	
			D57	4·9	3·11	11·4	7·24	35·6	

B. Final Experiments—*continued*

Anneal: Temperature (degrees C.)	Anneal: Duration (minutes)		Marks	Apparent Elastic Limit Kg/mm²	Apparent Elastic Limit tons/in²	Tensile Strength Kg/mm²	Tensile Strength tons/in²	Elongation %	Remarks
·552°	1	5	B58	4·2	2·67	12·3	7·81	28·3	(1)
			B59	4·2	2·67	11·8	7·49	27·4	
			B60	4·9	3·11	11·3	7·18	30·7	
			C58	5·2	3·30	11·2	7·11	35·7	
			C59	4·7	2·98	12·7	8·06	33·3	
			C60	5·7	3·62	11·5	7·30	35·0	
			D58	5·6	3·56	11·9	7·56	36·7	
			D59	5·0	3·17	11·4	7·24	35·7	
			D60	4·7	2·98	11·1	7·05	36·3	
		20	B58	3·6	2·29	9·7	6·16	38·6	
			B59	3·6	2·29	9·7	6·16	38·0	
			B60	3·5	2·22	10·0	6·35	36·6	
			C58	4·0	2·54	11·1	7·05	36·4	
			C59	4·0	2·54	11·2	7·11	34·0	
			C60	4·1	2·60	11·5	7·30	34·0	
			D58	4·2	2·67	11·1	7·05	38·0	
			D59	3·9	2·48	11·1	7·05	37·0	
			D60	4·1	2·60	11·0	6·98	36·4	
·604°	1	5	B61	5·6	3·56	11·4	7·24	31·7	
			B62	4·2	2·67	11·8	7·49	27·4	
			B63	5·1	3·24	12·1	7·68	31·7	
			C61	4·7	2·98	12·4	7·87	24·0	
			C62	4·8	3·05	12·2	7·75	32·7	
			C63	5·2	3·30	12·5	7·94	34·0	
			D61	6·0	3·81	11·8	7·49	34·0	
			D62	5·7	3·62	11·4	7·24	35·0	
			D63	5·6	3·56	11·8	7·49	36·0	
		20	B61	3·1	1·97	10·1	6·41	38·4	
			B62	3·3	2·10	10·0	6·35	37·0	
			B63	3·7	2·35	10·0	6·35	36·4	
			C61	3·4	2·16	11·0	6·98	34·4	
			C62	4·0	2·54	11·2	7·11	35·0	
			C63	3·9	2·48	11·3	7·18	36·2	
			D61	4·1	2·60	11·1	7·05	41·0	
			D62	3·3	2·10	11·1	7·05	35·0	
			D63	3·9	2·48	11·1	7·05	40·0	

APPENDIX V

Laboratoire d'Essais mécaniques, physiques, chimiques et de machines.

République Française.
Ministère du Commerce, de l'Industrie, des Postes et des Télégraphes.
Conservatoire des Arts et Métiers.

Paris, March 12th, 1919.

Report of Test No. 13463 on the requisition of Major Grard, technical inspector of metallurgical aviation materials, Paris.

Registered, Jan. 29th, 1919.

Object. Tensile and Shock tests on test pieces of aluminium subjected to thermal treatment.

Nature of Samples submitted.

A series of tensile and a series of shock test pieces. Each series consists of metal having two degrees of cold work, namely :—

100 % marked B_1.
300 % marked B_2.

Metal, having each degree of cold work, has been annealed under the following conditions :—

All the test pieces requiring the same anneal were pierced with a hole at one end and threaded on to the same piece of wire, 6–8 mm. apart, so as to be immersed simultaneously in the annealing bath, which was continuously stirred.

Shock test pieces requiring the same anneal were placed in baskets of iron wire of large mesh, and immersed in the bath at the same time as the corresponding tensile test pieces.

Results.

Dimensions of Tensile Test Pieces.

Between shoulders	Thickness	= 10 mm.
	Length	=100 mm.
	Breadth	=·15 mm.
	Approximate area	=150 sq. mm.

The area of cross section has been accurately calculated for each test piece.

Gauge length $=\sqrt{66{\cdot}67S}=100$ mm.

Dimensions of Shock Test Pieces: 55×10×10 mm.

A round groove, 2 mm. in depth, leaving a residual thickness of 8 mm.

Impact machine: 30 kg. m. Charpy pendulum.

VARIATION IN TEMPERATURE ABOUT THE REQUIRED TEMPERATURE DURING THE COURSE OF THE EXPERIMENT

Anneal	Bath	Duration (minutes)	Temp. required (degrees C.)	Temperature after . . . . . . minutes (degrees C.)																Mean Temp. of Anneal
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Preliminary	Oil	5	200	206	205	203·5	202	202	201	—	—	—	—	—	—	—	—	—	—	204
		10		200	198	197	197	197	198	198·5	199	199	199	199	—	—	—	—	—	198·7
		15		198	196	195·5	195·5	195·5	196·5	198	199·5	201	202·5	202·5	202·5	202·5	202	202	202	199·5
	Oil	2	350	355	355	355	—	—	—	—	—	—	—	—	—	—	—	—	—	355
		5		355	350	350	350	350	350	—	—	—	—	—	—	—	—	—	—	351·2
		10		350	345	345	345	350	350	350	350	350	355	355	—	—	—	—	—	350·4
	Salt	2	500	500	495	495	—	—	—	—	—	—	—	—	—	—	—	—	—	496
		5		500	500	500	505	505	505	—	—	—	—	—	—	—	—	—	—	501·2
		10		505	505	505	505	505	505	505	505	505	500	500	—	—	—	—	—	504
Final	Oil	6	100	102	102	101	101	100	99	99	—	—	—	—	—	—	—	—	—	100·5
			125	125	126	126·5	126·5	127	127·5	127·5	—	—	—	—	—	—	—	—	—	126·5
			150	150	151·5	154·5	154	148·5	149	150	—	—	—	—	—	—	—	—	—	151
			175	177·5	177	178	178·5	179	179·5	179·5	—	—	—	—	—	—	—	—	—	178·5
			200	203	202·5	199·5	199·5	199·5	198·5	199	—	—	—	—	—	—	—	—	—	200·5
			225	225	224	223	223·5	223·5	229	226·5	—	—	—	—	—	—	—	—	—	224
			250	250	250	249·5	250·5	252	253	254	—	—	—	—	—	—	—	—	—	251·5
	Oil up to 300° Salt from 325°	4	275	275	275	275	271	274	—	—	—	—	—	—	—	—	—	—	—	274
			300	301	299	299·5	299·5	300	—	—	—	—	—	—	—	—	—	—	—	300
			325	325	324	325	327	329	—	—	—	—	—	—	—	—	—	—	—	326
			350	350	348	348	349	351	—	—	—	—	—	—	—	—	—	—	—	349·5
			375	375	370	372	375	375	—	—	—	—	—	—	—	—	—	—	—	373·5
			400	400	395	400	405	405	—	—	—	—	—	—	—	—	—	—	—	401
			425	425	420	425	428	430	—	—	—	—	—	—	—	—	—	—	—	426
			450	450	440	450	455	450	—	—	—	—	—	—	—	—	—	—	—	448·5
	Salt	2	475	480	475	480	—	—	—	—	—	—	—	—	—	—	—	—	—	477·5
			500	500	495	498	—	—	—	—	—	—	—	—	—	—	—	—	—	497
			525	525	520	520	—	—	—	—	—	—	—	—	—	—	—	—	—	521
			550	555	550	550	—	—	—	—	—	—	—	—	—	—	—	—	—	551
			575	580	575	580	—	—	—	—	—	—	—	—	—	—	—	—	—	577·5
			600	605	600	600	—	—	—	—	—	—	—	—	—	—	—	—	—	601

PRELIMINARY TESTS *

Series	Anneal: Temp. (degrees C.)	Anneal: Duration (minutes)	Marks	Apparent Elastic Limit: Kg/mm²	Apparent Elastic Limit: tons/in²	Tensile Strength: Kg/mm²	Tensile Strength: tons/in²	Elongation %	$\frac{S-s}{S}$ Reduction	Briuell Hardness (using ball, 10 mm. in diameter) 500 Kg.: Diam. (mm.)	500 Kg.: Hardness No.	1000 Kg.: Diam. (mm.)	1000 Kg.: Hardness No.
B1 100 % cold work	200	5	64	12·5	7·94	13·6	8·64	11·5	0·40	4·10	36·0	5·75	35·0
		10	68	12·1	7·68	13·9	8·83	8·3	0·41	4·00	38·0	5·60	37·2
		15	71	12·5	7·94	13·0	8·25	13·0	0·39	4·10	36·0	5·75	35·6
	350	2	72	3·7	2·35	10·4	6·60	36·0	0·59	5·00	23·8	6·70	24·8
		5	73	3·9	2·48	10·6	6·73	38·8	0·58	4·95	24·4	6·55	26·2
		10	74	3·7	2·35	10·8	6·86	36·8	0·63	5·00	23·8	6·50	26·6
	500	2	125	3·6	2·29	10·8	6·86	33·6	0·58	5·10	22·8	6·60	25·6
		5	128	3·9	2·48	10·8	6·86	35·0	0·59	5·00	23·8	6·60	25·6
		10	131	3·6	2·29	11·5	7·30	36·0	0·64	4·90	24·9	6·40	27·6
B2 300 % cold work	200	5	135	13·2	8·38	14·7	9·33	9·4	0·41	4·05	37·0	5·65	36·4
		10	139	12·9	8·19	14·8	9·40	7·2	0·38	4·05	37·0	5·60	37·2
		15	142	13·1	8·32	14·5	9·21	10·8	0·48	4·05	37·0	5·60	37·2
	350	2	143	3·4	2·16	10·5	6·67	36·8	0·58	5·00	23·8	6·60	25·6
		5	144	3·3	2·10	10·5	6·67	36·8	0·59	5·05	23·3	6·65	25·2
		10	145	3·3	2·10	8·5	5·40	37·2	0·59	4·95	24·4	6·60	25·6
	500	2	196	3·8	2·41	11·1	7·05	32·8	0·57	4·90	24·9	6·50	26·6
		5	199	3·7	2·35	11·1	7·05	32·2	0·59	4·95	24·4	6·50	26·6
		10	202	3·4	2·16	11·5	7·30	35·5	0·59	4·90	24·9	6·50	26·6

* These tests have been carried out with a view to investigating the minimum length of time necessary for complete anneal at any given temperature.

As a result of these preliminary tests, the following experimental conditions have been adopted:

Duration of anneal (minutes)	Temperature
6	100°—250° (inclusive)
4	275°—450° ,,
2	450°—600° ,,

SERIES B1. (100 % COLD WORK)

Anneal		Marks	Tensile Properties										Shock Properties	
			Apparent Elastic Limit		Tensile Strength		Elongation %	$\frac{S-s}{s}$ Reduction	Brinell Hardness (using 10 mm. ball)				Shock Resistance $\frac{Kg.m}{cm^2}$	Angle of Rupture (degrees)
									500 Kg.		1000 Kg.			
Temp. (degrees C.)	Duration (minutes)		$\frac{Kg}{mm^2}$	$\frac{tons}{in^2}$	$\frac{Kg}{mm^2}$	$\frac{tons}{in^2}$			Diam. (mm.)	Hardness	Diam. (mm.)	Hardness		
—	—	61	13·3	8·45	14·9	9·46	8	0·42	4·05	37	5·60	37·2	4·4	Un-broken
As received		62	13·4	8·51	14·4	9·14	8	0·39	4·15	35	5·60	37·2	3·6	
	Long.	63	13·3	8·45	14·9	9·46	8·3	0·37	4·15	35	5·60	37·2	4·5	38
		64	—	—	—	—	—	—	—	—	—	—	4·3	
		65	14·9	9·46	15·6	9·91	6·2	0·33	4·10	36	5·50	38·6	3·5	Un-broken
	Trans.	66	13·6	8·64	15·2	9·65	6·8	0·35	4·05	37	5·50	38·6	3·8	
		67	12·9	8·19	15·4	9·78	6·9	0·34	4·10	36	5·50	38·6	3	
		69	13·4	8·51	14·7	9·33	7·5	0·34	4·20	34·5	5·60	37·2	3·3	34
100·5°	6	70	13·3	8·45	14·6	9·27	7·5	0·36	4·15	35·0	5·75	35	4	
		71	—	—	—	—	—	—	—	—	—	—	3·8	
		72	—	—	—	—	—	—	—	—	—	—	3·3	
126·5°	6	73	—	—	—	—	—	—	—	—	—	—	4·4	
		74	—	—	—	—	—	—	—	—	—	—	4·4	
		75	11·6	7·37	14·5	9·21	7·2	0·33	4·15	35	5·60	37·2	4·3	
151°	6	76	11·8	7·49	14·4	9·14	9·3	0·41	4·05	37	5·65	36·4	4·3	
		77	11·8	7·49	14·3	9·08	9·5	0·42	4·15	35	5·70	35·6	4·4	
		78	12·4	7·87	14·1	8·95	10·3	0·42	4·15	35	5·60	37·2	4·0	
178·5°	6	79	11·8	7·49	14·0	8·89	10·2	0·40	4·20	34·5	5·70	35·6	5	
		80	12·6	8·00	13·8	8·76	9·3	0·37	4·10	36	5·70	35·6	4·6	
		81	11·5	7·30	13·9	8·83	11·5	0·38	4·20	36	5·80	34·4	5	
200·5°	6	82	11·9	7·56	13·7	8·70	11·7	0·40	4·10	36	5·80	34·4	5	
		83	11·4	7·24	13·7	8·70	9·1	0·45	4·10	35	5·80	34·4	4·2	
		84	11·3	7·18	13·4	8·51	12·0	0·51	4·10	36	5·80	34·4	5	
224°	6	85	10·8	6·86	13·1	8·32	12·2	0·47	4·10	36	5·80	34·4	5	

326°	4	96	—†	—	10·3	6·54	37·5	0·57	5·0	23·8	6·70	24·8	6·6	unbroken
		97	—	—	10·4	6·60	37·2	0·57	4·95	24·4	6·70	24·8	6·7	
		98	—	—	10·3	6·54	30·2	0·57	4·90	24·9	6·70	24·8	6·5	
349·5°	4	99	—	—	10·5	6·67	38	0·57	4·90	24·9	6·60	25·6	6·3	
		100	—	—	10·5	6·67	37	0·58	5	23·8	6·65	25·2	6	
		101	—	—	10·4	6·60	34	0·55	5	23·8	6·60	25·6	6	
373·5°	4	102	—	—	10·7	6·79	35·2	0·58	5	23·8	6·60	25·6	6·4	
		103	—	—	10·5	6·67	35·6	0·59	5·10	22·8	6·60	25·6	6	
		104	—	—	10·5	6·67	30·5	0·55	5·05	23·3	6·60	25·6	7·1	
401°	4	105	—	—	11·0	6·98	35	0·60	4·90	24·9	6·55	25·2	9·1	
		106	—	—	10·6	6·73	37·5	0·57	4·95	24·4	6·60	25·6	8	
		107	—	—	11·0	6·98	36·2	0·57	4·95	24·4	6·60	25·6	8	
426°	4	108	—	—	11·0	6·98	38	0·60	4·95	24·4	6·50	26·6	9·6	
		109	—	—	10·6	6·73	36	0·57	5	23·8	6·60	25·6	8	
		110	—	—	10·6	6·73	28	0·47‡	5	23·8	6·55	26·2	8·3	
445·5°	4	111	—	—	11·4	7·24	36·2	0·62	4·90	24·9	6·40	27·6	8·5	
		112	—	—	10·8	6·86	29·5	0·56	4·95	24·4	6·60	25·6	8·5	
		113	—	—	11·1	7·05	35	0·57	4·90	24·9	6·50	26·6	8·9	
477·5°	2	114	—	—	10·9	6·92	32·2	0·52	5	23·8	6·55	26·2	8·3	
		115	—	—	10·7	6·79	36·5	0·55	5	23·8	6·55	26·2	8·8	
		116	—	—	10·8	6·86	32·5	0·49	5·05	23·3	6·55	26·2	9·5	
497°	2	117	—	—	10·8	6·86	32·5	0·53	4·90	24·9	6·50	26·6	8·7	
		118	—	—	10·9	6·92	30·4	0·57	4·90	24·9	6·55	26·2	9·1	
		119	—	—	10·9	6·92	34	0·57	4·90	24·9	6·50	26·6	8·9	
521°	2	120	—	—	10·9	6·92	33·5	0·57	4·90	24·9	6·60	25·6	9·1	
		121	—	—	10·8	6·86	31·8	0·56	5·0	23·8	6·65	25·2	9·1	
		122	—	—	11·2	7·11	33·2	0·57	4·90	24·9	6·60	25·6	8·9	
551°	2	123	—	—	10·9	6·92	24·2	0·43‡	4·95	24·4	6·50	26·6	8·9	
		124	—	—	11	6·98	32·2	0·54	4·95	24·4	6·50	26·6	9·1	
		125	—	—	—	—	—	—	—	—	—	—	9·5	
577·5°	2	126	—	—	11·6	7·37	32·8	0·54	4·85	25·4	6·40	27·6	9·8	
		127	—	—	11·4	7·24	29·5	0·49	4·90	24·9	6·40	27·6	9·6	
		128	—	—	—	—	—	—	—	—	—	—	9·1	
601°	2	129	—	—	11·6	7·37	34	0·57	4·85	25·4	6·40	27·6	8·9	
		130	—	—	11·5	7·30	30	0·50	4·85	25·4	6·40	27·6	9·5	
		131	—	—	—	—	—	—	—	—	—	—	9·5	

* Tensile test piece faulty.
‡ Tensile test piece superficially scaly.

† Above this temperature the Elastic Limits lie between 3 and 3·5 kg. per sq. mm. (1·90 and 2·22 tons per sq. in.)

SERIES B2. (300 % COLD WORK)

Anneal		Marks	Tensile Properties						Brinell Hardness (10 mm. ball)				Shock Properties	
			Apparent Elastic Limit		Tensile Strength		Elongation %	$\frac{S-s}{S}$ Reduction	500 Kg.		1000 Kg.		Shock Resistance $\frac{Kg.m}{cm^2}$	Angle of Rupture
Temp. (degrees C.)	Duration (minutes)		$\frac{Kg}{mm^2}$	$\frac{tons}{in^2}$	$\frac{Kg}{mm^2}$	$\frac{tons}{in^2}$			Diam. (mm.)	Hardness	Diam. (mm.)	Hardness		
As received	Long.	132	14·5	9·21	15·8	10·03	7	0·34	4·20	34·5	5·40	40·2	4·2	
		133	16·1	10·22	16·1	10·22	8	0·30	4	38	5·40	40·2	4	
		134	15·8	10·03	15·8	10·03	7	0·31	3·90	40	5·50	38·6	3·5	
		135	—	—	—	—	—	—	—	—	—	—	3·5	
	Trans.	136	14·2	9·02	16·4	10·41	6·5	0·38	3·75	44	5·40	40·2	3·4	
		137	14·6	9·27	16·6	10·54	6	0·36	3·75	44	5·35	41·2	3	
		138	14	8·89	16·7	10·60	6·5	0·32	3·85	41	5·30	42	3·1	
		139	—	—	—	—	—	—	—	—	—	—	3·5	
100·5°	6	140	14	8·89	15·9	10·10	8	0·36	3·90	40	5·40	40·2	4·6	
		141	14·3	9·08	15·8	10·03	7·5	0·40	3·90	40	5·40	40·2	4·4	
		142	—	—	—	—	—	—	—	—	—	—	4	
126·5°	6	143	—	—	—	—	—	—	—	—	—	—	4·2	
		144	—	—	—	—	—	—	—	—	—	—	4·2	
		145	—	—	—	—	—	—	—	—	—	—	4	
151°	6	146	13·6	8·64	15·4	9·78	7	0·32	4·05	37	5·55	38	5	
		147	14·2	9·02	15·3	9·73	9	0·31	3·90	40	5·50	38·6	3·7	
		148	13·9	8·83	15·6	9·91	7·5	0·32	3·90	40	5·50	38·6	4·2	
178·5°	6	149	13·5	8·57	15·2	9·65	9·3	0·45	3·95	39	5·50	38·6	4	
		150	13·6	8·64	15	9·52	8·5	0·40	3·95	39	5·50	38·6	3·3	
		151	13·6	8·64	15·1	9·59	9·5	0·41	4	38	5·50	38·6	3·5	
200·5°	6	152	12	7·62	14·7	9·33	10	0·48	4	38	5·60	37·2	5	
		153	12·8	8·13	14·5	9·21	10	0·40	4	38	5·55	38	4·2	
		154	12	7·62	14·8	9·40	11·5	0·41	4	38	5·50	38·6	4·6	
224°	6	155	11·9	7·56	14·1	8·95	12·4	0·42	4·10	36	5·65	36·4	5·8	
		156	12·2	7·75	14·1	8·95	10	0·43	4	38	5·65	36·4	4·2	
		157	12·5	7·94	14·6	9·27	14	0·53	4	38	5·60	37·2	5	
251·5°	6	158	12	7·62	13·3	8·45	14·8	0·46	4·10	36	5·70	35·6	6·3	
		159	12	7·62	13·6	8·64	13	0·44	4·10	36	5·70	35·6	5·5	
		160	11·6	7·37	13·4	8·51	14·8	0·42	4·15	35	5·70	35·6	6	
274°	4	161	10·3	6·54	12·8	8·13	17·9	0·51	4·20	34·5	5·80	34·4	5·8	
		162	11·1	7·05	12·9	8·19	18·3	0·48	4·25	33·6	5·80	34·4	6	
		163	10	6·35	12·8	8·13	17	0·47	4·25	33·6	5·80	34·4	6·3	
300°	4	164	6·1	3·87	11·3	7·18	30	0·57	4·70	27·2	6·20	29·6	6·5	
		165	6·1	3·87	10·9	6·92	27	0·51	4·60	28·4	6·25	29	6·5	
		166	6·4	4·06	11	6·98	30·5	0·52	4·70	27·2	6·30	28·6	6·5	
		167	3·4	2·16	10·4	6·60	33	0·57	4·90	24·9	6·60	25·6	7·1	

326°	4	168	4	2·54	10·2	6·48	36	0·55	5	23·8	6·65	25·2	6·9	unbroken
		169	3·6	2·29	10·3	6·54	42	0·62	4·95	24·4	6·65	25·2	6·9	
		170	—*	—	10·3	6·54	43	0·60	5	23·8	6·70	24·8	6·5	
349·5°	4	171	—	—	10·4	6·60	35·8	0·57	5	23·8	6·70	24·8	6·3	
		172	—	—	10·4	6·60	33	0·59	4·95	24·4	6·65	25·2	6·5	
		173	—	—	10·6	6·73	37·2	0·58	5	23·8	6·65	25·2	7·1	
373·5°	4	174	—	—	10·5	6·67	36·5	0·57	4·95	24·4	6·55	26·2	8·5	
		175	—	—	10·7	6·79	40·6	0·59	4·90	24·9	6·60	25·6	7·4	
		176	—	—	10·8	6·86	33·8	0·57	5	23·8	6·55	26·2	8·3	
401°	4	177	—	—	10·9	6·92	35	0·57	4·90	24·9	6·60	25·6	7·6	
		178	—	—	10·9	6·92	35	0·58	4·90	24·9	6·60	25·6	8·3	
		179	—	—	10·7	6·79	35	0·60	4·90	24·9	6·55	26·2	8·5	
426°	4	180	—	—	10·9	6·92	36·5	0·60	4·90	24·9	6·60	25·6	8·2	
		181	—	—	10·9	6·92	36·3	0·60	5	23·8	6·60	25·6	9·8	
		182	—	—	10·8	6·86	37	0·59	5	23·8	6·55	26·2	9·1	
448·5°	4	183	—	—	11	6·98	38	0·60	5	23·8	6·60	25·6	7·6	
		184	—	—	11	6·98	38	0·57	4·85	25·4	6·55	26·2	8·5	
		185	—	—	10·9	6·92	36·5	0·56	5	23·8	6·70	24·8	8·3	
477·5°	2	186	—	—	11	6·98	34	0·60	4·95	24·4	6·55	26·2	8·9	
		187	—	—	10·9	6·92	38·5	0·60	4·95	24·4	6·50	26·2	9·1	
		188	—	—	11·2	7·11	36	0·59	5	23·8	6·50	26·6	9·9	
497°	2	189	—	—	11·3	7·18	35	0·57	4·90	24·9	6·50	26·6	8·5	
		190	—	—	10·8	6·86	39	0·63	4·95	24·4	6·55	26·2	8·3	
		191	—	—	11·1	7·05	30·8	0·53	4·90	24·9	6·50	26·6	9·5	
521°	2	192	—	—	10·9	6·92	37·5	0·61	5	23·8	6·60	25·6	9·5	
		193	—	—	11·3	7·18	34·5	0·64	4·85	25·4	6·40	27·6	9·6	
		194	—	—	11·2	7·11	36	0·58	4·90	24·9	6·60	25·6	9·6	
551°	2	195	—	—	11·6	7·37	36·1	0·61	4·85	25·4	6·40	27·6	9·8	
		196	—	—	—	—	—	—	—	—	—	—	9·5	
		197	—	—	11·3	7·18	32·7	0·59	4·85	25·4	6·40	27·6	9·1	
577·5°	2	198	—	—	11·5	7·30	35	0·64	4·90	24·9	6·40	27·6	9·9	
		199	—	—	—	—	—	—	—	—	—	—	10·3	
		200	—	—	11·2	7·11	34·1	0·61	4·90	24·9	6·45	27	9·8	
601°	2	201	—	—	11·3	7·18	34·8	0·59	5	25·8	6·45	27	10·1	
		202	—	—	—	—	—	—	—	—	—	—	10·1	

* Above this temperature, the Elastic Limits lie between 3 and 3·5 kg. per sq. mm. (1·90 and 2·22 tons per sq. in.).

(Signed) Major, Director of Testing Laboratories.

APPENDIX VI

Paper by Lt.-Col. Grard on the Thermal Treatment of Alloys of Aluminium of Great Strength

Presented to L'Académie des Sciences, by Henri Le Chatelier, Membre de l'Institute, on Sept. 22nd, 1919*

THE alloys investigated have the following mean composition :—

Copper	3·5 to 4 %
Magnesium about	0·5 %
Manganese	0·5 to 1 %
Aluminium+alumina+impurities .	by difference,

and correspond with the type of light alloy of great strength known as " Duralumin."

The object of this paper is to state the results of the investigation on the variation in the mechanical properties of the worked alloy with the temperature of anneal after cold work and with the rate of cooling subsequent to this anneal.

(a) *Method of Heating.*

By immersion in oil or a salt bath (sodium nitrite, potassium nitrate), the alloy was heated to a series of temperatures, rising by fifty degrees from the normal temperature up to 500°.

(b) *Method of Cooling.*

Three rates of cooling were employed, namely :—

Rate (i). Very slow cooling in bath (maximum fall in temperature, 100° per hour).
Rate (ii). Cooling in air.
Rate (iii). Cooling by immersion in water at 20°, i.e. quenching in water.

During the first eight days after cooling, tests were carried out, and showed that the molecular state underwent no change in air during this period, when rate of cooling (i), as above defined, had been employed.

On the other hand, the use of rates (ii) or (iii) involves, in the open air during these eight days, certain molecular transformations, which are more profound in the case of rate (iii) (quenching in water) than in that of rate (ii) (cooling in air).

* *See* " Comptes rendus hebdomadaires des Séances de l'Académie de Sciences," Vol. CLXIX, No. 13, Sept. 29th, 1919 (mécaniques, physiques).

These changes, inappreciable for annealing temperatures up to 300°, become more pronounced, for both rates of cooling, with rise of annealing temperature.

After eight days, the mechanical properties remain approximately the same, although we cannot actually foresee the ultimate variations in the future.

In every case, all the tests given below were carried out, whatever the temperature of anneal and rate of cooling, eight days after the completion of cooling.

The experiments carried out show, for the three rates of cooling considered, two particularly interesting annealing temperatures, namely, 350° and 475°.

Corresponding with each of these temperatures and for any of the three rates of cooling, there is a maximum Elongation and Shock Resistance ; but, for the anneal at 350°, there is a minimum of the other mechanical properties (Tensile Strength, Elastic Limit, and Hardness), whilst there is a maximum of these latter properties for the anneal at 475°.

In the following table which summarises the results—

Tensile Strength = the greatest stress reached during the test, expressed in kilograms per sq. mm. of initial sections, or in tons per sq. in.

Elastic Limit = Apparent Elastic Limit.

Elongation = % Elongation after rupture, using the formula of the type :—

$\frac{L^2}{S} = 66{\cdot}67$ where L = gauge length.
,, S = initial section.

Shock Resistance = Shock Resistance or "Resilience"—the number of kilogram metres per sq. cm., necessary to cause the rupture by impact of a bar 10×10×53·3 mm. with a median notch 2 mm. broad, 2 mm. deep, and with the bottom rounded off to 1 mm. radius.

Temp. of Anneal (degrees C.)	Rate of Cooling	Tensile Strength $\frac{Kg}{mm^2}$	Tensile Strength $\frac{tons}{in^2}$	Elastic Limit $\frac{Kg}{mm^2}$	Elastic Limit $\frac{tons}{in^2}$	Elongation %	Shock Resistance $\frac{Kg.m}{cm^2}$
350°	(i)	20	12·7	6	3·81	20	6
	(ii)	20	12·7	7	4·44	20	4–5
	(iii)	20	12·7	9	5·71	15	3
475°	(i)	28	17·78	12	7·62	16	4
	(ii)	32	21·32	18	11·42	18	4
	(iii)	40	25·4	20	12·7	20	4

Two treatments stand out, namely :—

(1) That giving the metal a maximum ductility, or a softening treatment, consisting in annealing at 350°, followed by cooling, rate (i) (100° per hour).

(2) That giving the metal maximum tensile properties, or the final treatment, consisting in annealing at 475°, followed by cooling, rate (iii) (quenching in water).

Double Quenching from 475°.

Double quenching from 475°, carried out each time under the conditions previously defined, gives duralumin the following properties :—

Tensile Strength =40 kg. per sq. mm. (25·4 tons per sq. in.)
Elastic Limit =23 kg. per sq. mm. (14·6 tons per sq. in.)
% Elongation =22
Shock Resistance=5 kg. m. per sq. cm.

This constitutes the optimum final heat treatment.

The industrial practice of a softening anneal (annealing at 350°, followed by cooling rate (i) (100° per hour)), which has just been investigated as described in this paper, shows that this intermediate treatment is of real use for drawing and pressing, ensuring, at the same time, minimum waste, maximum output, and maximum life of tools.

We give a set of curves* of the mechanical properties corresponding with different anneals, followed by cooling, rate (iii) quenching in water, which show the maxima and minima for this particular heat treatment.

* *See* Fig. 53, page 101.

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